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Effect of gas on deepwater marine sediments

Effet du gaz sur les sédiments marins en eau profonde

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ABSTRACT: Existing and future offshore developments in deepwater face risks due to geohazards such as submarine sliding. Evaluation of deepwater slope stability requires a fundamental understanding of the soil behaviour. This paper describes the development and verification of material models to predict the response of soil containing gas or gas hydrates. Gassy soils and gas hydrates are relatively common in deepwater sediments and both have a significant affect on the soil response to changes in temperature and/or pressure.

RÉSUMÉ: Les développements existants et à venir en eaux profondes sont assujettis à des catastrophes géologiques tel qu'un glissement du sous-sol marin. L'évaluation d'une stabilité de pente du sous-sol marin nécessite la connaissance fondamentale du comportement du sol. Cette communication décrit le développement et la vérification des lois de comportement des sols contenant du gaz ou des hydrates de gaz. Les sédiments en eaux profondes contiennent souvent des sols gazeux ou des hydrates qui sont très sensibles aux variations de températures et de pressions.

1 INTRODUCTION

The development of deepwater oil and gas fields is progressing in continually deeper water along the continental slopes towards the abyssal plains in the Gulf of Mexico, offshore Brazil and West Africa, in the Norwegian and Caspian Seas and other areas worldwide. In several areas, mapping of the seabed along the continental slopes has revealed large prehistoric slides and seepage features like mud volcanoes and pockmarks associated with gas and fluid escape to the seabed. This raises the concern about the present and future stability of these areas.

The triggering mechanisms and the evolution of prehistoric slides are in many cases not well understood, and the assessment of today's risk for further sliding and the connected consequences are associated with considerable uncertainty. This may delay or prevent the exploitation of oil and gas resources and/or entail considerable extra cost connected to protective measures to avoid or reduce the risk and the consequences of sliding.

The need for improved understanding of triggering and sliding mechanisms involved in deepwater slides, specifically the material behaviour of gassy soils has been identified as an important research area. This paper describes the development and verification of material models to predict the response of soils containing gas or gas hydrates.

2 BACKGROUND

Offshore soils frequently contain bubbles of undissolved gas, usually methane but occasionally carbon dioxide, hydrogen sulfide, or ethane. These gases usually originate from biogenic (bacterial activity) or petrogenic (thermal alteration) processes, but may also originate from volcanic or hydrothermal sources, or may be primordial gas. Gas may also result from the destabilization of gas hydrates. Gas hydrates are ice-like compounds composed of water and methane gas that occur under high pressure and low temperature conditions. The presence of even a small amount of free gas could have significant implications on the behavioural and engineering soil properties such as shear strength, compressibility characteristics, and liquefaction potential.

Gas can occur in the seabed in three ways: in solution in the pore water, undissolved in the form of gas filled voids, or as gas hydrates. In the first case, gas will have little effect on the physical properties of the seabed unless the ambient pressures are reduced. In the second case, gas will affect the engineering properties of the seabed. In the third case, gas will become hazardous only if the hydrate melts.

Undissolved bubbles of gas form only when the volume of gas exceeds the maximum volume of gas that can be dissolved in the pore liquid at the particular pressure and temperature conditions. In offshore soils, the degree of saturation is usually greater than approximately 85%, which results in a soil structure where the water phase is continuous and the gas phase is discontinuous (i.e. occluded bubbles). In fine-grained soils the gas forms relatively large bubbles that are surrounded by a saturated matrix while in coarse-grained soils the gas forms relatively small bubbles that exist within the pore spaces, as illustrated in Figure 1.

Previous research on the geotechnical implications of gas in offshore sediments has focused on sample disturbance, equilibrium effects, shear strength, consolidation, acoustics, and liquefaction potential. The majority of this research has been either theoretical, experimental, or a combination of both. For additional information on gassy soils, the reader is referred to the following papers: Esrig and Kirby (1977), Wheeler (1988a,b), Sills et al. (1991), Rad et al. (1994), Grozic (1999), and Grozic et al. (1999, 2000).
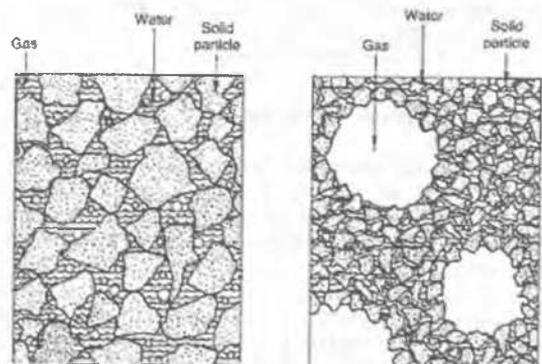

Figure 1. Structure of coarse and fine grained soils containing occluded gas bubbles (from Wheeler 1988a).

The aim of this research program was to develop and verify material models to describe the behaviour of soils containing gas and gas hydrates subjected to a reduction of pressure or an increase in temperature. The material models will ultimately be implemented into a slope stability program which will be used to investigate the role of gas and gas hydrates in the triggering and sliding of deepwater submarine slopes.

3 GASSY SOIL RESPONSE

The presence of gas will affect the behaviour and engineering properties of the soil, especially when subjected to changes in stress or temperature. In deepwater marine sediments, an undrained or partly drained stress change can be induced rapidly due to earthquake loading or removal of mass (e.g. slumping or sliding), or slowly due to eustatic and isostatic sea level reductions. Temperature changes may result from sedimentation on a long-term basis or from heat generated from producing oil wells on a short-term basis. A reduction in pressure and/or an increase in temperature will cause gas to exsolve from the pore fluid and free gas to expand. Both gas exsolution and expansion create excess pore pressures and result in a decrease in the effective stress and shear strength. The dissipation of the excess gas and fluid pressures depends on the drainage conditions and the soil permeability.

3.1 Predicted gassy soil response

3.1.1 Solubility and compressibility

The presence of free gas will affect the compressibility of a soil element. If the pore gas and liquids are miscible to some extent then the compressibility will be a function of the pressure, temperature, compressibility of the gas, and solubility of the gas in the liquid.

The compressibility of free gas is described by Boyle's law, which states that the volume V of a gas varies inversely with its pressure P at a constant temperature T. The combination of Boyle's law with other gas laws forms the ideal gas law:

$$PV = nRT \tag{1}$$

where n is the number of moles of gas and R is the molar gas constant.

The solubility of a gas in a particular liquid, denoted by Henry's constant, will depend on the pressure, temperature and salinity of the pore water. Henry's constant can be estimated from published data (Cramer 1984). For this project a value of 0.001 mol/litre/atm was used.

When the pore water is fully saturated with dissolved gas, a pressure reduction will lead to reduced solubility and cause exsolution of the dissolved gas into free gas. If the pore water is only partly saturated, a pressure reduction will lead to a gradual increase in the degree of gas saturation of the pore water, until full saturation is achieved. With further pressure reduction exsolution of gas will begin.

The theoretical development of water saturation versus pore water pressure is shown in Table 1 for 100%, 80%, 50% and 30% initial dissolved gas saturation.

3.1.2 Effect of free gas on soil response to temperature and total stress changes

Assuming that the pore water pressure and the free gas pressure are equal or respond equally to stress changes, incompressible pore water and mineral grains, and constant temperature, the following continuum and stress equilibrium conditions apply:

$$\frac{\partial u}{K_g(p,T)} \cdot n \cdot (1 - S_w) = \frac{\partial \sigma'}{M(\sigma')} \tag{2}$$

gas volume reduction = volume change of soil

Table 1. Predicted degree of pore water saturation as a function pressure reduction and initial methane gas saturation at 12 MPa pressure.

Pressure	Initial CH₄ saturation of pore water			
	100%	80%	50%	30%
MPa	S	S	S	S
12	100%	100%	100%	100%
10	100%	100%	100%	100%
8	99%	100%	100%	100%
6	98%	99%	100%	100%
4	96%	97%	99%	100%
3	93%	95%	98%	100%
2	89%	91%	95%	98%
1	79%	82%	89%	94%
0.75	73%	77%	85%	91%

where n is the porosity, S_w is the degree of saturation, ∂u is the change in pore pressure, K_g is the compressibility of the gas, $\partial \sigma'$ is the change in effective stress, and M is the confined compression modulus of the soil.

$$\partial p = \partial u + \partial \sigma' \tag{3}$$

Substituting Equation (3) into (2) leads to:

$$\partial \sigma' = \frac{\partial p}{1 + \dfrac{K_g(p,T)}{M \cdot n \cdot (1 - S_w)}} \tag{4}$$

which describes the effective stress change due to a change in the total pressure.

3.2 Laboratory verification tests for free gas

A laboratory program was carried out with the objective of verifying the material model presented in Section 3.1. One test in the oedometer apparatus was performed to determine: a) the influence of a total pressure decrease on the degree of saturation of a gassy specimen; and b) the response of a clay with free gas to undrained changes in overburden stress.

3.2.1 Laboratory testing procedures

A large oedometer ring containing a partially consolidated specimen of Rønne Kaolin clay was assembled into a triaxial cell and the back pressure increased to 12 MPa. Saline water saturated with dissolved methane gas was circulated through the specimen in order to replace the existing pore fluids.

After further consolidation, the verification testing was commenced. The test comprised of first performing an undrained unload/reload loop at saturated conditions to determine the soil response. Then the back pressure was reduced causing gas exsolution and expansion to occur thus forming bubbles within the specimen. Another undrained unload/reload loop was performed to determine the soil response at the new saturation and pressure conditions. Continuation of the test involved further back pressure reductions followed by an undrained unload/reload loop at each pressure level.

A photograph of the testing equipment is shown in Figure 2.

3.2.2 Results of laboratory tests on gassy specimens

The results of the specialized high pressure oedometer test on the gassy specimen are presented in Figure 3. In Figure 3(a) the degree of saturation is plotted versus water pressure. This plot shows that as the back pressure was reduced, gas exsolution and expansion occurred causing the amount of free gas to increase and the degree of saturation to decrease. A relatively large decrease in pressure was required to lower the degree of saturation from 100% to approximately 95%. After the degree of saturation drops below 95% (i.e. 5% free gas) then relatively small decreases in pressure resulted in larger changes in the degree of saturation. These results indicate that gas expansion is a more dominant process than gas exsolution.

2290

Figure 3(b) presents the change in effective stress normalized by the change in total stress plotted versus the degree of saturation. A relation between the change in effective stress and degree of saturation is indicated; as the degree of saturation decreases there is a greater change in the effective stress. The test data plots relatively close to a straight line indicating that it may be possible to predict the effective stress change for a given initial degree of saturation and applied change in total pressure.

3.3 Comparison of laboratory results with predicted response

The results of the laboratory test were predicted using Equation (4) by prescribing a change in total pressure and then calculating the change in effective stress. Equation (4) was used in conjunction with the compressibility and solubility of the gas and liquids to determine the effect of a total pressure reduction on the porosity and degree of saturation.

The results of the model prediction are presented in Figure 4 as plots of degree of saturation versus water pressure and normalized effective stress change versus water pressure. The results of the gassy oedometer test described above are included on the plot. Figure 4(a) shows that the predicted response matches the laboratory tests relatively well at high pressures. At lower water pressures, the model predicts a lower degree of saturation than observed in the laboratory data. Figure 4(b) presents the predicted response as normalized change in stress versus pore water pressure. The model predictions match the laboratory results well at high pressures but are not able to capture some of the changes in effective stress undergone by the laboratory specimen at lower back pressures.

One possible reason for the discrepancies between the laboratory and model results is that the specimen pore water was not initially 100% replaced with methane gas saturated water. This could happened due to preferential flow paths being created or water bonded to the clay particles which is not being replaced. It is also possible that the volume of gas saturated water circulated through the specimen was not enough to flush the distilled water from the pores of the clay specimen. Figure 5 shows the influence of the initial saturation of the water with dissolved methane on the specimen degree of saturation results. As the percentage of methane dissolved in the water is decreased the model predicts a higher degree of saturation (i.e. gas exsolution will not occur until the pressure has been reduced to a value at which the pore water becomes saturated with methane gas). The results of the laboratory test are also included in this figure. The laboratory results plot close to an initial dissolved methane saturation of 50%, indicating that it is unlikely all the pore water in the specimen was completely replaced with methane saturated water.
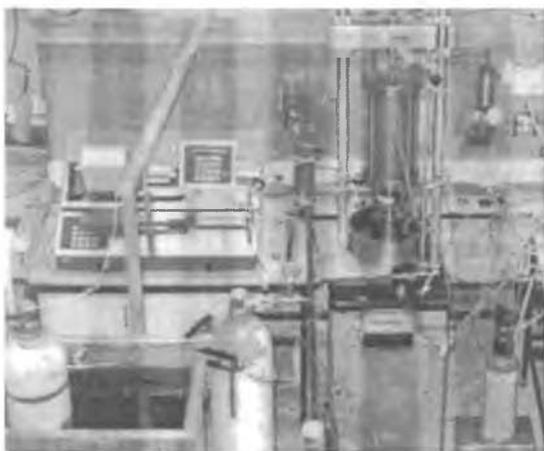
The comparison of the predicted and laboratory results show acceptable agreement indicating that the numerical model performs well. The results also indicate that at high degrees of saturation, little change in the effective stress or saturation will
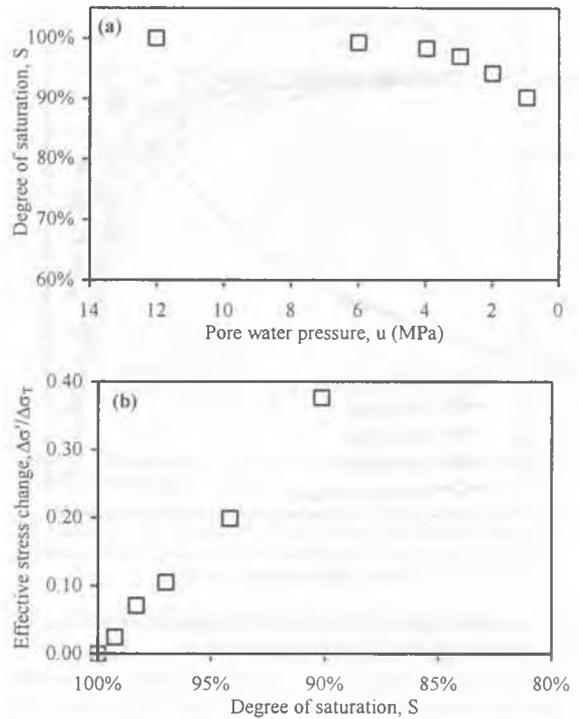

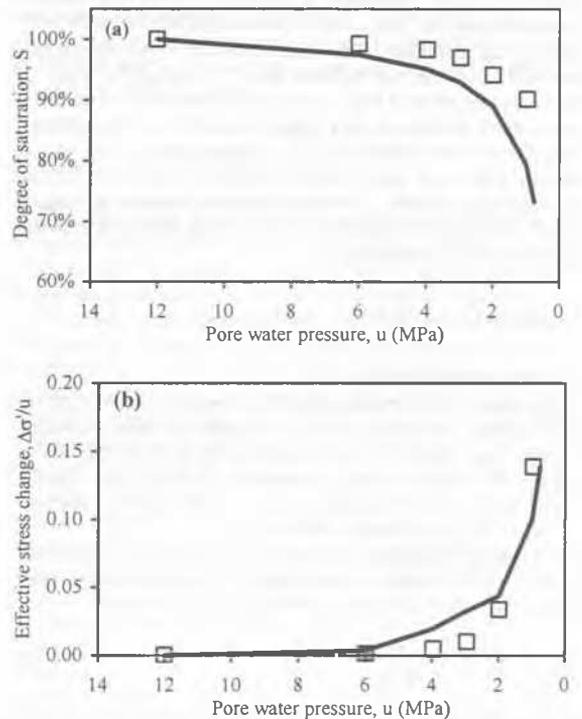Figure 3. Results of free gas verification test in high pressure oedometer.

Figure 4. Comparison of predicted and observed free gas response.

occur for relatively large total pressure changes. However, once the degree of saturation drops below approximately 95% (i.e. 5% free gas), both the model and laboratory results indicate that relatively small changes in pressure can result in significant gas expansion which increases the pore pressures and reduces the effective stresses. The results also indicate that not all the pore fluid of the specimen was initially replaced with methane saturated water.
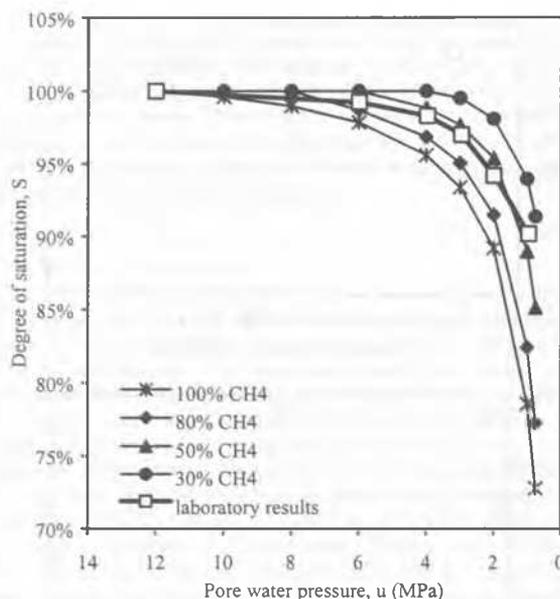

Figure 2. Photograph of high pressure oedometer apparatus for gassy soil testing at NGI.

Figure 5. Predicted degree of pore water saturation as a function of pressure reduction and initial methane gas saturation.

Figure 6. Hydrate stability diagram for two geothermal gradients and three water depths.

4 GAS HYDRATE RESPONSE

Gas hydrates, ice-like structures composed of gas and water, can form in deepwater marine sediments. Several gases are known to form hydrates but methane gas hydrates are the most common. A hydrate consists of molecules of water tied together by hydrogen bonds to form a lattice into which mobile molecules of methane are absorbed. One volume of water will enclathrate (absorb) 207 volumes of methane gas. For example, 1 m³ of hydrate contains about 0.9 m³ of water and 164.6 m³ of methane gas at standard conditions, and approximately 1.1 m³ of methane gas at 1000 m water depth and 2°C. Dissociation of 1 m³ of gas hydrate in 1000 m of water would therefore result in a volume increase of about 100%. This considerable increase in volume will cause an increase in the pore pressure and a reduction in the effective stress in the sediments.

4.1 Predicted gas hydrate response

4.1.1 Gas hydrate stability

Temperature and pressure affect the thermodynamic stability of gas hydrates. Oceanic hydrates are stable in zones extending downward from the seafloor in water depths greater than 400 m to a depth determined by the geothermal gradient. The hydrate stability zone is a function of the water depth, seafloor temperature, and geothermal gradient.

For offshore conditions, the following pressure-temperature correlation can be used to determine the hydrate stability zone (Kamath et al. 1987) for methane hydrates in pure water:

$$\ln P = 38.98 - \frac{8533.8}{T + 273.15} \quad (5)$$

where P is the pressure in kPa, and T is the temperature in °C (for $T \geq 0°C$). For hydrates in sea water (35 ppt salt), the temperature is shifted approximately $-1.5°C$, i.e. salt water tend to inhibit hydrate formation to a certain extent (Dickens and Quinsby-Hunt, 1994).

For a given site with water depth z and a given geothermal gradient, the critical temperature can be calculated and the thickness of the gas hydrate stability zone determined. Figure 6 shows the temperature versus depth plot for two geothermal gradients and the critical temperature for three different depths.

At pressure and temperature conditions outside the stability range, dissociation or melting of gas hydrates will occur. Pressure decreases 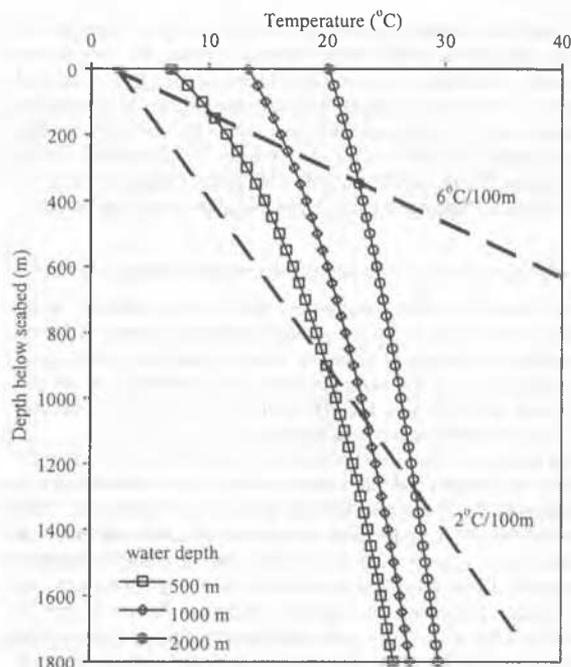may occur due to sea level variations or removal of mass by slumping or sliding. Temperature increases may develop due to increased sea water temperatures, due to sedimentation, or due to heat from producing oil wells.

4.1.2 Effect of methane hydrate on soil response to temperature and total stress changes

Dissociation of gas hydrate will release gas and generate a volume expansion. If the temperature/heat transport and the pressure change processes are fast compared with pore pressure dissipation processes, the excess pore pressure and reduction in effective stress can be estimated as follows:

$$-0.13 \cdot n \cdot (1 - S_w) + \frac{164.6 \cdot n \cdot (1 - S_w) \cdot 1atm \cdot T_{eq}}{298.15K \cdot p_{eq}} = -\frac{\Delta \sigma'}{M(\sigma')} \quad (6)$$

where n is the soil porosity, S_w is the degree of water saturation, $(1-S_w)$ is the degree of saturation of gas hydrates assuming no free gas in the hydrate stability zone, T_{eq} is the equilibrium temperature of gas hydrate in K, p_{eq} is the equilibrium pressure of gas hydrate in atm, $\Delta \sigma'$ is the change in effective stress caused by melting of gas hydrate, and M is the confined compression modulus of soil. The first term represents the difference between the hydrate volume and melted water volume (1.0 m³ – 0.87 m³), the second term represents the volume of released gas at equilibrium temperature and pressure and the final term represents the volume change of the soil.

If it is assumed that the pore water pressure and the pore gas pressure are equal then:

$$\Delta p = \Delta u + \Delta \sigma' \quad (7)$$

where Δp is the change in total stress and Δu is the change in pore pressure.

For a pure temperature induced melting, $\Delta p = 0$ and $\Delta u = -\Delta \sigma'$, and thus:

$$\Delta \sigma' = -\Delta u = M(\sigma') \cdot n \cdot (1 - S_w) \left[0.13 - 164.6 \frac{T_{eq}}{298.15} \frac{1atm}{p_{eq}} \right] \quad (8)$$

Equation (8) is valid until the effective stress reduction reaches the overburden pressure, resulting in zero effective stress, or until the gas starts to form bubbles.

4.2.1 Preparation of gas hydrate specimens

Original studies on the properties of gas hydrates used tetrahydrofuran (THF) hydrates, which form a structure II hydrate (Parameswaran et al. 1989, Sego & Wittebolle 1984) and results in a specimen consisting of frozen soil and THF hydrate. Synthetic hydrates have also been formed using trichlorofluoromethane, a refrigerant commonly referred to as R11, which results in a structure that can include both hydrates and free water. More recently experimental researchers have formed gas hydrates in the laboratory by exposing sand specimens to carbon dioxide saturated water (Buffett & Zatsepina 2000) or exposing sand to methane gas (Wright et al. 1998). The conditions for formation of these hydrates are much closer to in situ hydrate formation conditions.

In this still ongoing experimental program, an endeavor was made to form gas hydrates in the triaxial apparatus. Following normal mounting and consolidation procedures for triaxial testing, a specimen of Rønne Kaolin clay was consolidated to temperature and pressure conditions slightly outside the hydrate stability range. Saline water saturated with dissolved methane gas was then circulated through the specimen with the intent to replace some of the pore fluid with gas saturated pore fluid. Following circulation of approximately two times the volume of voids, the temperature of the specimen was reduced thereby bringing the middle section of the specimen into the hydrate stability zone. The top and bottom portions of the specimen were kept just outside of the hydrate stability range to prevent hydrate plugging of circulation lines. Circulation of gas saturated water continued while the temperature and pressure conditions were kept constant and within the hydrate formation zone. As the circulated pore fluids reached the zone of lowered temperature, the solubility of methane increased and the degree of methane gas saturation could have dropped below 100%. This could have inhibited or even prevented the formation of methane gas hydrates.

In addition to the usual triaxial measurements, internal axial deformation, specimen temperature, and electrical resistance were measured during formation and testing.

4.2.2 Gas hydrate testing procedures

The gas hydrate testing program is ongoing. To date, one triaxial test has been performed in which gas hydrates were attempted to be formed and then dissociated twice. The first hydrate formation/dissociation cycle took approximately 15 days to complete and the second cycle approximately 12 days. The entire test took over 45 days.

One cycle consisted of gas hydrate formation, described above, and subsequent dissociation (melting). Dissociation of the hydrates was achieved by stopping the cooling system, closing all drainage, and allowing the specimen to return to room temperature. As the temperature increases above the hydrate stability zone, melting of generated hydrate should occur and water and free gas be released.

The quantity of gas hydrate formed within the specimen was estimated using two methods. The first method involved monitoring the electrical resistance. The electrical resistance of a soil specimen will increase when gas hydrates are present and the amount of increase is related to the percentage of the void spaces occupied by hydrates (Booth et al. 1998, Buffett & Zatsepina 2000). The second method involved theoretically estimating upper and lower bounds of the number of moles of methane that could be transported into the specimen during the circulation time.

4.2.3 Results of laboratory tests on gas hydrates

The dissociation part of the gas hydrate testing resulted in a pore pressure increase corresponding to approximately 10% reduction of the effective consolidation stress. The estimated content of gas hydrate that could have been produced lies in the range of 1 to 3 percent of the volume of voids.

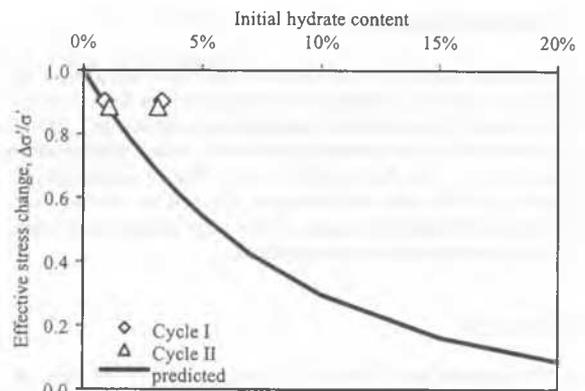Figure 7 shows the normalized effective stress change versus

Figure 7. Comparison of predicted and observed stress change during hydrate dissociation.

the initial hydrate content. The upper and lower bounds of the estimated hydrate content are plotted for Cycles I and II.

4.3 Comparison of laboratory results and predicted response

The predicted pore pressure response and effective stress reduction is shown in Figure 7. The upper and lower bounds of the hydrate content, determined from the laboratory tests, are also plotted. The model and laboratory results show that dissociation of gas hydrates causes a reduction in the effective stress. The model indicates that the greater the amount of initial hydrate present, the greater the reduction of stress upon dissociation.

The test results indicate a correspondence between the predicted and observed responses. However, there is still considerable uncertainty regarding estimates of hydrate content and further testing and analysis is required for verification of the gas hydrate melting model.

5 SUMMARY AND CONCLUSIONS

This paper describes the development and verification of two material models which predict the soil response to changes in pressure and temperature; one for soils containing free and dissolved gases, and one for soils containing gas hydrates.

The gassy soil model and laboratory results show that as the total vertical pressure is decreased the degree of saturation decreases and the effective stress change during undrained unloading/reloading increases. For initial degrees of saturation between approximately 100% and 95%, relatively large changes in the vertical pressure result in small changes of the degree of saturation (i.e. little gas exsolves). However, once the degree of saturation drops below 95%, relatively small changes in the vertical pressure result in large changes in the degree of saturation. This observation indicates that although a reduction in pressure will cause both gas exsolution and expansion, at high pressures expansion is the dominant process for methane gas.

The gas hydrate model and laboratory results show that as gas hydrates dissociate, water and methane gas are released causing an increase in pore pressure and a decrease in effective stress. The model indicates that the greater the amount of gas hydrate initially present in the specimen, the greater the reduction of effective stress upon dissociation.

Understanding the material behaviour of soils containing gas and gas hydrates, combined with improved understanding of the physical processes and triggering mechanisms, will enable quantitative assessments of the risk of submarine sliding and its consequences. By assessing the risk of submarine sliding, the exploitation of oil and gas resources including the development of deepwater installations may be completed in a safe, timely, and cost-effective manner.

6 ACKNOWLEDGEMENTS

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