

A simple model for submarine slope stability analysis with gas hydrates

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Gas hydrates have been of interest for years, but as of late they have become increasingly considered as a potential energy source, a potential environmental impact, and a geohazard. This paper discusses the latter. A simple model was developed to analyse the impact of gas hydrate dissociation on the stability of submarine slopes as described by the factor of safety. Dissociation of gas hydrates will result in the release of large quantities of gas, which in undrained conditions will cause significant increase in the pore pressure, decrease in effective stress, and could ultimately result in soil failure. The model considers the water depth, seabed temperature, geothermal gradient, and quantity of gas hydrate as well as soil parameters such as void ratio and plasticity index. Results indicate that dissociation of even a relatively small percentage of gas hydrates can have a significant impact on the stability of a submarine slope. Further, the analysis shows that slopes located at shallower water depths will be more susceptible to instability due to hydrate dissociation.

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Introduction

Gas hydrates are unique compounds consisting of an ice-like substance composed of gas, most commonly methane, trapped within water molecules. Gas hydrates form and exist in locations where there is an ample supply of gas and the temperature and pressure requirements allow stability (Sloan 1998). Globally there are numerous locations where these criteria are met in permafrost areas and continental margin soils around the world. For example, within Canada's borders there are significant quantities of gas hydrates, both terrestrial and marine (Smith 2001).

Gas hydrates represent a significant geohazard that is of immediate importance to near and offshore developments. "Human activities and installations in regions of gas-hydrate occurrence must take into account the presence of gas hydrate and deal with the consequences of its presence" (Kvenvolden 2000). There are many examples of a possible connection between gas hydrates and submarine slope failures. Kvenvolden (1993; 1999) summarized slope failures on the continental slope and rise of the west coast of Africa, on the US Atlantic continental slope, in the fjords of British Columbia, and on the Alaskan Beaufort Sea continental margin. Several researchers have performed in-depth analyses of the Norwegian continental margin and Mienert et al. (2005), Jung & Vogt (2004), Vogt & Jung (2002), and Sultan et al. (2004a, 2004b) all suggest that gas hydrates

may have triggered one or more large submarine slides in this area.

Gas hydrates are stable under low temperatures and high pressures. The hydrate stability zone in marine environments is a function of the water depth, the seafloor temperature and the geothermal gradient. Any changes to the temperature and/or pressure, both at the surface and in the area adjacent to the hydrate, will affect the thickness of the stability zone. Although temperature and pressure are the main controls in the formation of gas hydrates and the thickness of the hydrate stability zone, other factors such as gas chemistry and gas availability will also alter the thickness and location of the hydrate stability zone.

At pressures and temperatures outside the hydrate stability range, dissociation (melting) of gas hydrates will occur. Dissociation will result in the release of water and methane gas but requires heat input. Complicating the dissociation process are the effects of time dependency, soil permeability, and diffusion. As dissociation occurs, the released gas and water create a volume expansion, which depending on the drainage conditions can cause an increase in the pore fluid (gas and water) pressures and a decrease in the effective stress. If the 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.

For decomposing gas hydrates to be a widespread cause of slope failure, three criteria must be met (Dillon & Max 2000): (1) gas hydrates must not only be present, but must be widespread as well; (2) slides must have originated in areas that are within the gas hydrate phase boundaries; and (3) soils of low permeability must be common at the base of the hydrate zones (to permit the build up of excess pore pressure that could lead to unstable slopes during sea-level falls).

In order to quantify the effects of gas hydrate dissociation, a numerical analysis has been undertaken. The dissociation of gas hydrates can stem from any change in the pressure/temperature regime in the hydrate stability zone and results in a significant volume change. The objective of this paper is to show the influence of gas hydrate dissociation on the stability of submarine slopes. In submarine slopes, the significant volume change occurring during hydrate dissociation combined with low permeability soils or hydrate seals result in rapid build up of excess pore pressures, which may induce or facilitate instability. The results of this numerical analysis highlight the factors which most influence stability of slopes containing gas hydrates.

Parametric Study

In order to assess which parameters contribute most to the instability of a slope undergoing gas hydrate dissociation a sensitivity analysis was conducted. The sensitivity analysis consisted of varying a single parameter, such as water depth, while keeping all other values at a constant value. Details of the geomechanical and slope stability models are found in the Appendix. The model inputs used in the parametric study are listed in Table 1; these values are synthetic in that they do not apply to one particular site, however they are based on data from submarine slopes found in the Beaufort Sea.

The parameters that were investigated are (1) melting rate and the number of steps to bring the analysis to complete dissociation; (2) water depth; (3) depth to failure surface; (4) hydrate content, along a simulated slope at two different water depths, and varying slope angles; (5) plasticity index; and (6) void ratio.

Melting rate

The geomechanical model allowed for different approaches to calculate the pore pressure; either by melting the gas hydrate in a single step or performing iterations where the gas hydrate was brought to complete dissociation in small increments. The incremental melting of the hydrate was performed by using hydrostatic pore pressures as the initial input and calculating the confined

Table 1. Values of parameters used in the sensitivity analyses.

Parameter	Value	Reference
Cohesion (kPa)	0	Crooks et al. (1986)
Frictional angle (°)	30	Crooks et al. (1986)
Unit weight of soil (kN/m ³)	16	Crooks et al. (1986)
Plasticity index	35	Christian and Morgenstern (1986)
Depth to hydrate (m)	50-850	Kayen and Lee (1991)
Water depth (m)	0-3500	Kayen and Lee (1991)
Slope Angle (degrees)	0-10	Kayen and Lee (1991)
Percent hydrate (%)	0-25	Majorowicz and Osadetz (2000)
Porosity	0.3-0.4	Collet (1993)
Geothermal gradient (°C/100m)	2-3	Weaver and Stewart (1982)
Bottom temperature (°C)	0-2	Weaver and Stewart (1982)

Table 1: Values of parameters used in the sensitivity analyses. The values used are for a generic slope located in the Beaufort Sea.

compression modulus, M , for no changes in effective stress. For each increment of hydrate dissociation the confined compression modulus was estimated using the change in effective stress resulting from the previous melting step. When the gas hydrate dissociation was induced in a single step, the geomechanical model used a constant value of the confined compression modulus which was estimated using hydrostatic pore pressures.

The variation of the factor of safety for different melting rates is shown in Fig. 1. This plot shows that when the gas hydrate is brought to complete dissociation through incremental melting the factor of safety does not drop as quickly as when the gas hydrate melting is induced in a single step. The generic slope used in the

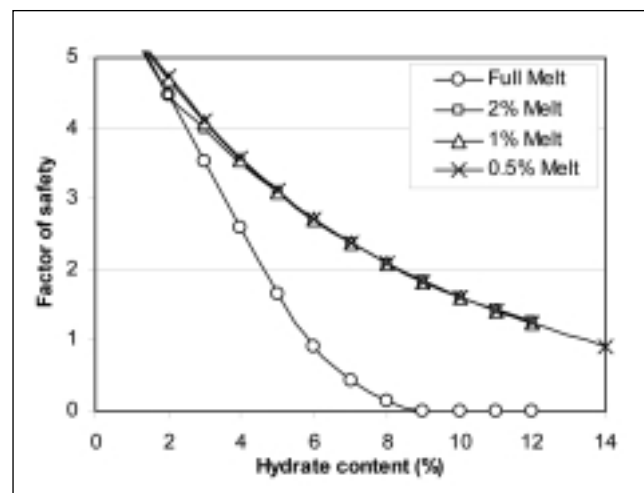


Fig. 1: Effect of melting rate on factor of safety.

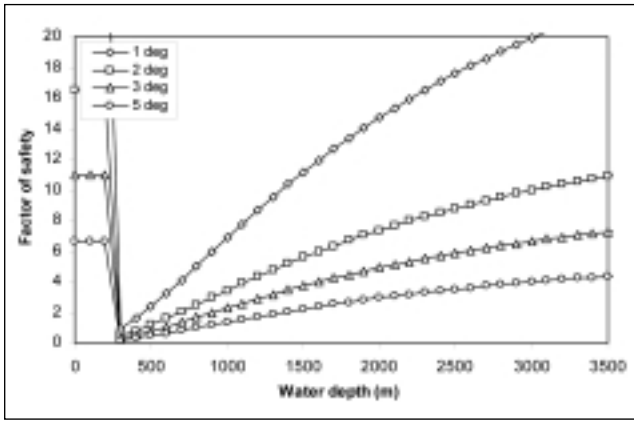


Fig. 2: Effect of increasing water depth on factor of safety for four slope angles with hydrate layer 200 m below seabed.

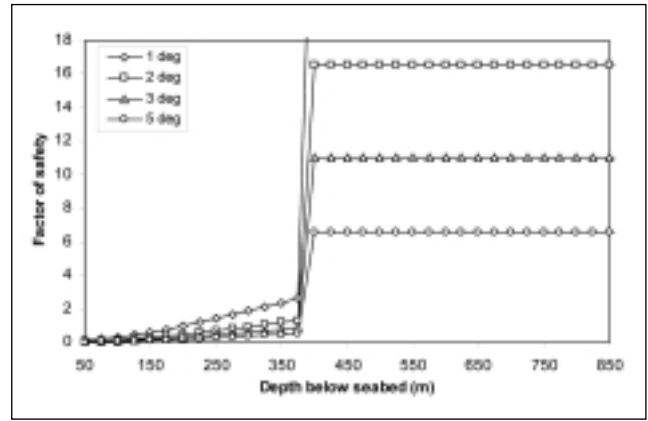


Fig. 3: Effect of increasing depth below seabed on factor of safety for four slope angles in 150 m of water.

study has a factor of safety of 6.34 without hydrates present. If the hydrates are dissociated in a single step (full melt) then the slope fails upon dissociation of 6% hydrates; while if the hydrates are dissociated in an incremental manner the slope does not fail until 14% hydrates have decomposed. The differences in slope behaviour are a result of the inclusion of the increase in pore pressures acting on the unmelted gas hydrate at each increment; the higher pressures act to compress the melting gas and retard the volume expansion or, in the undrained case, the increase of pressures. Because the incremental melting is believed to better capture the behaviour of natural gas hydrate dissociation, this method of incrementally dissociating the hydrate is used for all the analyses presented in the following sections. Specifically, increments of 0.5% hydrate dissociation are used as this rate will produce the most accurate and consistent results.

Water depth

This analysis investigated the effects of water depth on gas hydrate dissociation and the factor of safety. Seismic data from the Beaufort Sea area indicates that the base of the hydrate zone is located at approximately 200 m below the seabed (Kayen & Lee 1991). Thus, using the base of the hydrate layer located 200 m below the seabed and a 10% hydrate content (Majorowicz & Osadetz 2000), the factor of safety was calculated at discrete points at increasing water depths (see Fig. 2). At water depths from 0 to 300 m, there is not enough pressure for gas hydrates to form at 200 m below the seabed, thus the factor of safety is high and the slope is stable. The factor of safety then drops to well below one as the hydrate stability range is entered at a water depth of 300 m. This significant drop in the factor of safety indicates that the pore pressure generated by complete dissociation of the 10% hydrate is greater than the total stress acting at that point, therefore, little or no resistance to sliding is provided, i.e. zero effective stress.

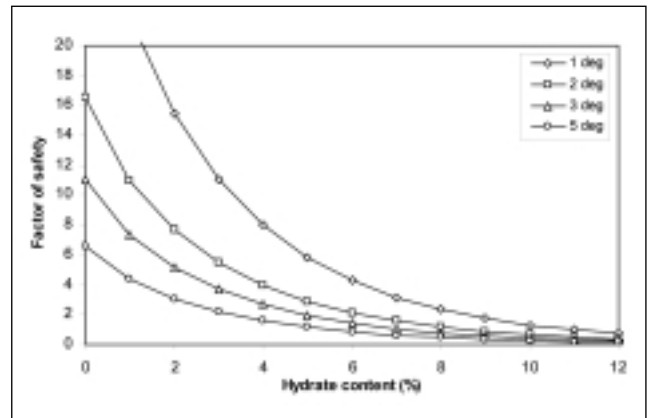


Fig. 4: Factor of safety using summation of discrete points on four simulated slopes for water depths ranging from 150m to 530m.

The factor of safety then begins to rise as the overburden stress increases, which decreases the magnitude of excess pore pressure generated by melting gas hydrates due to the higher pressure regime. These results show that gas hydrates will have the most detrimental effect on the stability of this slope in water depths ranging from approximately 300 to 700 m; or that stability will be most critical at or near the up-dip limit of the gas hydrate stability zone.

Depth below seabed

This analysis involved varying the depth of the hydrate layer below seabed and calculating the factor of safety. Assuming a water depth of 300 m and hydrate content of 10%, and then increasing the depth of hydrate below the seabed similar results to the water depth are produced (see Fig. 3). This figure illustrates that at shallow depths below the seabed gas hydrates have a greater impact on the factor of safety. This greater adverse effect is due to lower magnitude of overburden stress than that being applied to the gas released by the dissociation process. The lower the overburden, the greater the magnitude of pore pressure generated by dissocia-

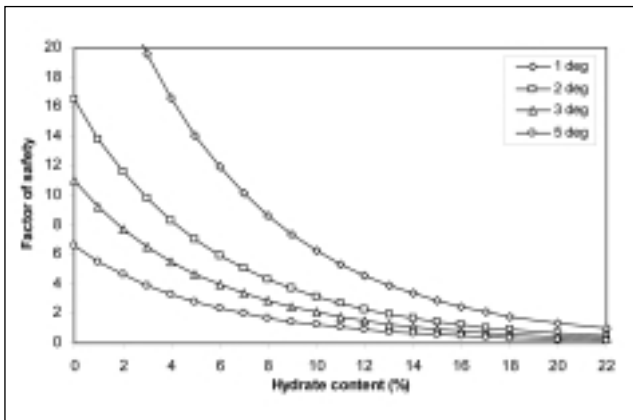


Fig. 5: Factor of safety using summation of discrete points on four simulated slopes for water depths ranging from 750m to 1130m.

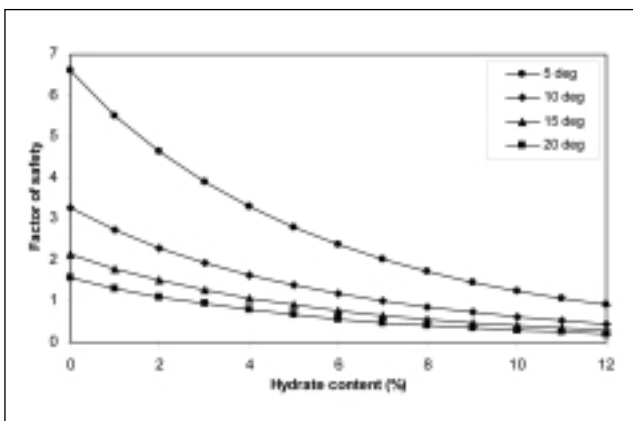


Fig. 6: Factor of safety using summation of discrete points on a simulated slope for water depths ranging from 750m to 1130m with greater slope angles.

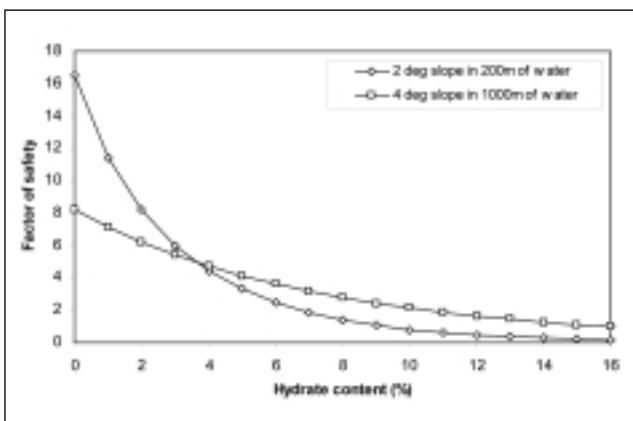


Fig. 7: Comparison of two slope angles in different water depths.

tion, thereby reducing the resistance to sliding. The factor of safety begins to rise as the overburden begins to exert more confining stress on the pressures generated by hydrate melting. As the hydrate becomes deeply buried within the soil (far right of the curves), the temperature rises above that required for hydrate stability and hydrates will no longer exist.

Gas hydrate content

The following section investigated the impact of hydrate content on the factor of safety of a generic slope. The factor of safety was calculated by summing the resisting and driving forces from the infinite slope equation at discrete points at increasing water depths.

The first case uses a hydrate depth of 200 m below the seabed and varying from 150 to 530 m water depths and the average factor of safety was calculated given increasing gas hydrate contents from 0 to 12% (See Fig. 4). It can be seen that with increasing gas hydrate contents the factor of safety drops quickly for all slope angles and by dissociation of 11% gas hydrates all the slopes have failed.

Using a water depth of 750 to 1130 m, the factor of safety was calculated using the identical situation as the shallow water slope (See Fig. 5). It can be seen that for greater water depths, the factor of safety still drops relatively quickly but not as fast as the shallower water depth. The decrease in effect on the factor of safety is due to the greater pressure exerted by the larger overburden on the dissociating gas hydrate. The excess pore pressure generated by the dissociation process becomes lesser in magnitude and has a lower impact on the factor of safety. For example in the shallower water depths the one degree slope at 5% hydrate has a factor of safety of 5.8 and fails by 11% hydrate. Then for the deeper water depth by 5% hydrate the one degree slope has a factor of safety of 14 and fails by 22%. This illustrates that a greater water depth has a stabilizing effect on a submarine slope when gas hydrates undergo dissociation.

The third case investigated the effect of steep slopes in deep water where the inputs were identical to the deep water slope. As expected, the steeper slopes are less stable even without the inclusion of gas hydrates as illustrated in Fig. 6. Because the slope is initially less stable, dissociation of even a small amount of gas hydrates can cause failure. For example, the one degree slope described in the preceding section failed upon dissociation of 22% gas hydrates, whereas a 10 degree slope only requires dissociation of 7% hydrates to induce failure. As the angle of inclination of the slope increases the factor of safety decreases; with dissociation of 12% gas hydrates all the slopes with angles greater than 5 degrees have failed.

Comparison of two slope angles in two water depths

This analysis was performed to explicitly show the effects of water depth on the factor of safety given gas hydrate dissociation. Two simulated slopes were analyzed with identical properties except for the water depth and slope angle. The shallow water depth (200 m) has a 2° slope and the deeper water depth (1000 m) has a 4°

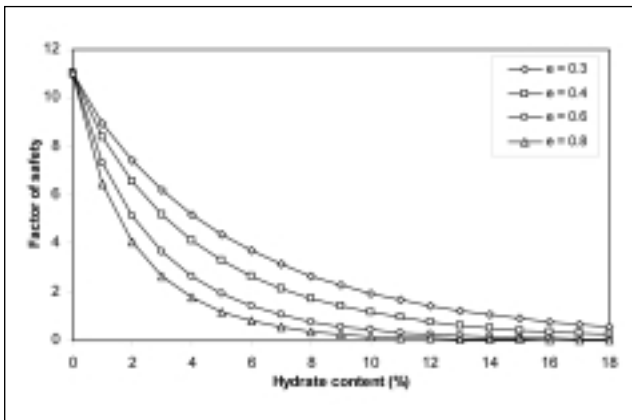


Fig. 8: Factor of safety on a simulated slope for water depths ranging from 150 to 530 m using varying void ratios.

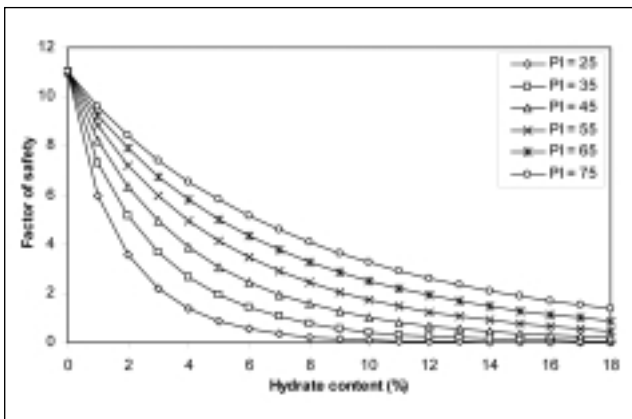


Fig. 9: Factor of safety on a simulated slope for water depths ranging from 150 to 530 m using varying plasticity indices.

slope. Fig. 7 shows the results of this analysis that a shallower slope with lower slope angle will fail before a steeper slope in a greater water depth. The 2° slope fails by 10% gas hydrate while the 4° slope fails at 16%. The depth of water exerts stress on the released gases and decreases the magnitude of the pore pressures generated by dissociation as the water depth increases. This analysis shows the importance of the water depth in which the hydrate exists, which is crucial for evaluating its impact on slope stability.

Effect of void ratio

Void ratio is an important parameter for the calculation of the excess pore pressure as it dictates the maximum quantity of gas hydrate which can exist within the pores and therefore the maximum quantity of hydrate potentially available for dissociation. The factor of safety was evaluated for a water depth of 150 to 530 m with the hydrate layer 200 m below the seabed, with a frictional angle of 30°, a cohesion of 0 kPa, and a plasticity of 35. As illustrated in Fig. 8, a soil with a higher

void ratio loses resistance to sliding with less quantity of gas hydrate, than a soil with a lower void ratio. For example, the case of a void ratio of 0.8 will have failed by approximately 6% gas hydrate, while a slope with a void ratio of 0.3 will take approximately 15% gas hydrate to cause failure. Therefore, the void ratio would be an important parameter to evaluate as accurately as possible a slope's susceptibility to failure due to gas hydrate dissociation. This sensitivity to void ratio is not necessarily a result of the model but should be indicative of the actual soil - gas hydrate interaction and behaviour.

Effect of plasticity index

Plasticity index was used as a substitution in the calculation of the excess pore pressure as a method of working around certain, difficult to quantify, parameters. As a result, it has become an important variable for this method of analysis. The plasticity index was varied from 25 to 75 and a factor of safety was calculated with increasing gas hydrate content. Fig. 9 indicates the significant variation of factor of safety with plasticity index given a certain hydrate content. For example, for a plasticity index of 25 the slope fails at 5% gas hydrate, while for a plasticity of 65 the slope would require approximately 18% gas hydrate in order for failure to occur. This significant variation of factor of safety with plasticity index stems from the use of the Wroth et al. (1979) correlation of swelling index with plasticity index. As a result this sensitivity of the factor of safety to the plasticity index could be considered a material property and not a mathematical model assumption. However, testing should be done to identify to what extent plasticity index would affect the strength of a dissociating soil. This testing would determine a more definite impact, as these results are only an approximation and not an exact prediction.

Discussion

There are numerous factors that can cause a slope to fail by either loss of soil strength or increase in shear stress. In this manuscript we have investigated gas hydrate dissociation as a potential source for submarine slope instability.

It has been shown that with increasing gas hydrate content within a submarine slope the factor of safety can be drastically reduced when the dissociation process occurs. The exact reduction in factor of safety will vary depending on the soil properties and the slope geometry involved. The results of this study indicate that gas hydrates will be most detrimental if they are located close to the up-dip limit of the stability zone and in shallower waters with less overburden stresses. There

are also two soil parameters that have a significant impact on the factor of safety of a submarine slope; void ratio and plasticity index. Void ratio will define the maximum amount of pore space available for gas hydrates to occupy, therefore the high sensitivity to void ratio would be indicative of actual gas hydrate behaviour and not a result of numerical modelling. The correlation between plasticity index and swelling index suggests that the high sensitivity to plasticity index would be actual behaviour, though the accuracy will depend on the acceptability of the correlation used.

These analyses present results which, in order to quantify the behaviour, required several assumptions. These assumptions are: (1) complete and instantaneous gas hydrate dissociation; (2) undrained soil behaviour; (3) gas hydrates located at a uniform depth below seabed and constant saturation along the failure plane; and (4) soil parameters and properties uniform throughout the slope.

The proposed model does not take into account possible time dependent effects of generation and dissipation of the pore pressures developed by gas hydrate dissociation. As gas hydrates dissociate excess pore pressures would develop at an unknown rate, simultaneously these pore pressures would potentially be dissipating through faults or other pathways. In maintaining simplicity, the model does also not account for the influence of the changing pressure and temperature on gas solubility or the endothermic nature of hydrate dissociation which will reduce the temperature. All these effects will decrease the magnitude of pore pressure build-up induced by hydrate dissociation and should be incorporated into further analyses.

Gas hydrates were assumed to be located at a constant depth below seabed and constant saturation along the failure plane. Since the failure surface being investigated is significantly longer than it is deep, any variation in the vertical direction would be negligible. Gas hydrates can form both in continuous layers, as well as in nodules and pockets. Sharma et al. (1992) describe gas hydrates found in the Beaufort Sea to be layered and in the Gulf of Mexico as nodules; therefore it is possible that the content of gas hydrates would vary along the failure plane. Current detection methods limit the accuracy of determining the spatial distribution of gas hydrates; however, as our in situ detection methods advance further research is required to account for the variation of hydrates on the slope stability.

Conclusions

Gas hydrates are ice-like compounds that represent a significant geohazard, placing offshore drilling and production facilities at risk. There is substantial evidence that links major seafloor collapses to the presence of gas hydrates. Theoretical evidence shows that dissociation of gas hydrates will result in increased fluid pressure, dilation of the soils, and the development of gas bubbles, all which will have the effect of substantially weakening the soils. This mechanism could be responsible for the triggering of submarine slope failures.

This research proposes a simple model to quantify the pore pressure increases due to dissociation of gas hydrates. The proposed model was incorporated into slope stability analyses; the results of which indicate that dissociation of gas hydrates could significantly reduce submarine slope stability. A parametric study showed that the factor of safety for a submarine slope containing gas hydrates will decrease with decreasing water depth, decreasing depth to hydrate below the seabed, and increasing percentage of hydrate within the soil. Also, using this method of analysis the void ratio and plasticity index will have a great effect on the resulting factor of safety. However, whether gas hydrate dissociation can singularly cause large-scale slope failures has yet to be concluded as there are typically a number of destabilizing processes within the vicinity of a failure.

Uncertainty in the processes causing submarine slope failures, combined with the widespread occurrence of gas hydrates in continental margin soils throughout the world's oceans, gives rise to the need to assess the effects of hydrate dissociation on the behaviour of submarine soils and their susceptibility to slope instability. Clearly more research is required before a quantitative understanding of the role of gas hydrates in the initiation and progression of submarine slope failures can be developed. Fundamental research is required in the areas of: 1) the behavioural properties of gas hydrate rich soil; 2) the dynamic equilibrium of gas hydrate rich soils including the effects of perturbations to this system; and 3) in situ detection and distribution of gas hydrates.

Results of further research could be applied to slope stability analysis to quantify the effects of gas hydrates on slope failures, thus providing the fundamental knowledge necessary to produce guidelines that identify seabed areas with a high risk of failure. By improving our knowledge of seabed conditions, risk of damage to existing structures and pipelines can be evaluated and potential offshore developments can be designed in a safe, cost-effective manner.

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Appendix – Stability Model

Geomechanical model

In order to quantify the impact of gas hydrate dissociation on submarine slope stability a material model for gas hydrate decomposition and the resulting pore pressures was developed. This model is an extension of previous work by Grozic & Kvalstad (2001).

The volume change due to gas hydrate dissociation and the corresponding increase in excess pore pressure was calculated from:

$$\Delta\sigma' = -\Delta u = M \cdot \left[n \cdot (1 - S) \left[0.13 - 164.6 \frac{T_2}{298.15} \frac{1 \text{ atm}}{P_2} \right] - \left(\frac{P_1}{P_2} - 1 \right) V_{G1} \right] \quad (1)$$

where T_2 is the equilibrium temperature of gas hydrate in Kelvin, P_2 is the equilibrium pressure of gas hydrate in atm, $\Delta\sigma'$ is the change in effective stress caused by melting of gas hydrate, n is the porosity, S is the degree of water saturation, Δu is the change in pore pressure, V_{G1} is the volume of the free gas at the previous pressure, P_1 is the pressure at the previous step, and M is the confined compression modulus of soil. This equation is based on each volume of hydrate producing 164.6 volumes of methane gas and 0.87 volumes of water at standard pressure temperature conditions (Max and Dillon 1998). The water phase is assumed to be incompressible and the compression of the gas phase to follow Boyle's law. Assuming undrained conditions, the change in effective stress is equated to the change in pore pressure.

The confined compression modulus is related to the coefficient of compressibility, a_v , by:

$$M = \frac{1 + e}{a_v} \quad (2)$$

where e is the void ratio. Dissociation results in a decrease in effective stress therefore using the consolidation model, the swelling index is more applicable than the compression index. The coefficient of compressibility can be related to the swelling index, C_s , through:

$$C_s = \frac{\Delta e}{\Delta \log \sigma'} = \frac{\Delta e}{\log(\sigma' + \Delta\sigma') - \log \sigma'} = \frac{\Delta e}{\log \left(\frac{\sigma' + \Delta\sigma'}{\sigma'} \right)} = \frac{\Delta e}{0.434 \ln \left(1 + \frac{\Delta\sigma'}{\sigma'} \right)} \quad (3)$$

Therefore the coefficient of compressibility becomes:

$$a_v = \frac{\Delta\sigma'}{\Delta\epsilon'} = \frac{0.434 \cdot C_s \cdot \ln \left(1 + \frac{\Delta\sigma'}{\sigma'} \right)}{\Delta\epsilon'} \quad (4)$$

As a result the confined compression modulus becomes:

$$M = \frac{(1 + e) \Delta\epsilon'}{0.434 \cdot C_s \cdot \ln \left(1 + \frac{\Delta\sigma'}{\sigma'} \right)} \quad (5)$$

Then using the correlation developed by Wroth (1979) for a given plasticity index, PI , and specific gravity, G_s ,

the compression index, C_c , can be approximated from:

$$C_c = \frac{PI \cdot G_s}{200} \quad (6)$$

Also according to Wroth (1979), a ratio of C_s/C_c would be 0.17 for a $PI = 15\%$ and 0.34 for $PI = 100\%$ and Equation (6) can be used to calculate C_s , assuming a linear relationship between the ratio of C_s/C_c and PI the swelling index can be calculated as:

$$C_s = (0.002 \cdot PI + 0.14) \cdot \left(\frac{PI \cdot G_s}{200} \right) \quad (7)$$

This substitution based around the plasticity index is used because plasticity index is a common and readily accessible term found in soil data, which facilitates the calculation of the confined compression modulus from Equation (5). For a complete derivation see Nixon (2005).

Slope stability model

The infinite slope equation is a relatively simple one dimensional method of slope stability analysis, which assumes a constant resisting and driving force along the base of an assumed planar failure surface. Because the resistance forces of the ends of the failure surface are neglected, the infinite slope equation is most applicable when the depth to failure surface is small and the slope is long; such is the case for most submarine slopes. The geomechanical model described above was coupled with the infinite slope model to produce a factor of safety for a submarine slope undergoing gas hydrate dissociation. First, the model checks to see whether gas hydrates could exist under the given conditions. The pressure temperature correlation published by Kamath et al. (1987) was used:

$$\ln P = 38.98 - \frac{8533.8}{T + 273.15} \quad (8)$$

where P is the pressure in kPa and T is the temperature in °C (for $T \geq 0^\circ\text{C}$).

If the conditions are within the gas hydrate stability zone, then the excess pore pressure (Equation (1)) resulting from a prescribed dissociation was added to the existing pore pressure. The total pore pressures, u , were used in the infinite slope equation to calculate a factor of safety from:

$$FS = \frac{c}{(\gamma \times H) \sin \beta \cos \beta} + \frac{(\gamma \times H - \gamma_w \times z) \cos \beta \tan \phi}{(\gamma \times H) \sin \beta} - u \times \frac{\tan \phi \cos \beta}{(\gamma \times H) \sin \beta} \quad (9)$$

where c is the cohesion, γ is the submerged unit weight of the soil, γ is the saturated unit weight of the soil, γ_w is the unit weight of water, H is the depth below seabed to the bottom of the hydrate layer, z is the water depth, β is the slope angle, ϕ is the friction angle of the soil, and u is the pore pressure. The use of this equation dictates that when the factor of safety is less than one the slope has failed, and greater than one the slope is stable.

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