Chapter 43
Stability of Fine-Grained Sediments Subject to Gas Hydrate Dissociation in the Arctic Continental Margin

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Abstract Significant venting of methane gas has been observed on the upper continental slopes of the Arctic Ocean, coinciding with the landward limit of the gas hydrate stability zone. It has been inferred that the methane gas venting is related to the dissociation of methane gas hydrate induced by the unprecedented Arctic warming that has occurred over the last 30 years. Historically, the influence of hydrate dissociation on sediment stability was considered in terms of hydrate dissociation increasing pore pressures, reducing effective stress and therefore sediment strength, leading to slope failures along these over pressurized layers. Recent evidence has shown that gas hydrate readily forms in clay-rich sediments as fracture-filled near-vertical veins, which upon dissociation gives rise to sediments exhibiting high water content, high sediment compressibility and very low shear strength. Thus gas hydrate dissociation in fine-grained sediments may lead to significant slope instabilities, which at present is poorly understood. Slope stability analyses carried out considering the potential influence of hydrate dissociation induced by warming of the Arctic slope suggest that instabilities are likely, with failures ranging from surficial sloughing to deep-seated failures. This paper highlights the importance of understanding the sediment processes in clay soils, and how dissociation of gas hydrate can induce instabilities through sediment softening and generation of excess pore pressure.

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43.1 Introduction

It is now globally recognized that anthropogenic induced climate change is occurring, with the greatest change observed in the Arctic region as reported by the Intergovernmental Panel on Climate Change (IPCC 2007). A possible consequence of this warming, especially in the Arctic Ocean, is the dissociation of methane gas hydrate, an ice-like crystalline compound that is stable under certain conditions of low temperature and high pressure that are typically found within deep marine sediments and in and beneath permafrost (Kvenvolden and Lorenson 2001). Methane gas hydrate sequesters large volumes of methane, a greenhouse gas; therefore dissociation of gas hydrate may release significant quantities of methane into the ocean and the atmosphere, exacerbating climate change (Archer et al. 2009). In addition, gas hydrate dissociation can lead to significant reduction in sediment strength leading to slope instability and submarine landslides (Mienert et al. 2005; Grozic 2009).

In this paper we investigate the influence of gas hydrate dissociation, resulting from Arctic Ocean warming, on sediment shear strength and the resulting impact that changes in sediment properties have on slope instabilities.

43.1.1 Climate Change and Arctic Hydrates

Gas hydrates are extensive within the Arctic region (Council of Canadian Academies 2008) located below onshore permafrost, sub-sea permafrost and on slopes of the continental margin. Given predicted warming scenarios hydrate dissociation below onshore permafrost (>300 m below the ground surface) and sub-sea permafrost on the Arctic shelf (~200 m below the current sea level) is unlikely to occur over the next millennia (Ruppel 2011). The cold waters of the Arctic Ocean allow gas hydrate to form within the sediments on the slopes of the Arctic continental margin at shallower water depths than observed on other margins with the upper limit of hydrate stability zone (HSZ) tapering out near the seafloor ~300 m water depth (Fig. 43.1). Therefore, hydrate-bearing sediments in this area are the most sensitive to warming in the near future (Ruppel 2011).

Multiple plumes of gas bubbles, predominantly methane, emanating from the seabed on the West Svalbard margin of the Arctic Ocean have been observed that coincide with the calculated present day landward limit of the HSZ (Westbrook et al. 2009). It is suggested that the 1 °C rise the Arctic Ocean has experienced at this water depth over the last 30 years has led to the dissociation of gas hydrate within the sediment leading to the observed methane gas expulsions from the seabed (Thatcher et al. 2013). In addition, similar observations of active methane gas venting have also been observed within the Beaufort Sea area of the Arctic Ocean at water depths where the HSZ thins out (Paull et al. 2011).

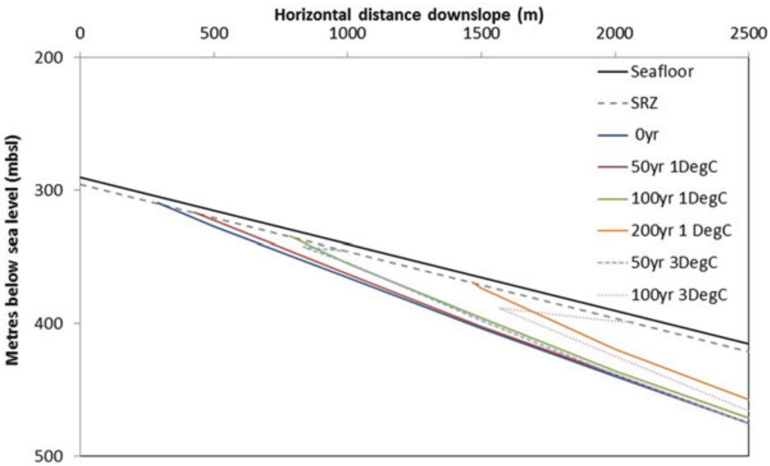

Fig. 43.1 Modeled slope geometry highlighting water depth to seafloor, sulfate reduction zone (*SRZ*), initial base of hydrate stability (0 year) and subsequent changes in the base of hydrate stability for two ocean bottom temperature increases (1 °C and 3 °C) with time

43.1.2 Hydrate in Fine-Grained Sediments

Recent insights from pressure cores where hydrate stability conditions within the sediment during core recovery are maintained have shown that in fine-grained sediments (typical for shallow marine sediments in the Arctic) hydrate readily forms as fracture-filled near-vertical veins with average hydrate saturations of ~20–30 % (Rees et al. 2011). These veins can vary considerably in thickness (<0.5 mm up to 6 mm) and be fibrous in nature with veins showing terminal forking and branching. Results from the limited testing of the pressure core samples suggest that these hydrate veins increase in apparent sediment strength (Yun et al. 2010) inhibiting normal consolidation of the sediment; stiffer hydrate veins support the overburden stress acting on the sediment.

Upon dissociation of the hydrate the host sediment exhibits high void ratios and water contents leading to high compressibility (Kim et al. 2013) and low undrained shear strength, s_u (Priest et al. 2014), compared to normal sediments at corresponding depths. In addition to the low strength of the host sediment, hydrate dissociation can lead to the development of excess pore pressure within the sediment (Sultan et al. 2004; Grozic 2009). Both of these factors may lead to slope instabilities in regions where gas hydrate exists.

43.2 Slope Stability Modeling

Hydrate dissociation through warming of the Arctic Ocean over the next 100 years (IPCC 2007) may lead to significant changes in sediment behavior over this time. To investigate the influences of these changes on slope stability 2-D limit equilibrium slope stability analyses were carried out using Slope/W (a commercially available slope stability analysis program) that considers total shear resistance and mobilized shear stresses along a slip surface to compute factors of safety. In our analyses both undrained and drained soil behavior were considered.

43.2.1 Slope Profile

In our analyses a slope width of 2500 m starting at a water depth to the seafloor of 290 m with an initial slope angle of 3°, corresponding to average slope geometry in the Arctic Ocean, was modeled (Fig. 43.1). To account for typical sulfate reduction processes that inhibit gas hydrate formation in shallow sediments a 5 m thick hydrate-free zone was located directly below the seafloor (Biastoch et al. 2011). The initial base (0 year) of the HSZ was determined using CSMGem code (Sloan and Koh 2008) for an ocean bottom temperature of 0 °C at the seafloor, pore water salinity of 3.5 wt.% and a geothermal gradient of 0.87 °C/m. The geothermal gradient is at the high end of reported values (Phrampus et al. 2014) leading to a reduction in the thickness of the HSZ, which results in a larger volume of sediment subject to hydrate dissociation with time during a warming event, and thus represents a worse case scenario.

Changes in the base of the HSZ with time (Fig. 43.1) due to an increase in ocean bottom temperatures were taken from the results of Reagan et al. (2011) who carried out detailed 2-D simulations of hydrate dissociation. Their simulations took into account the endothermic nature of hydrate dissociation and increase in hydrate stability due to increases in pore pressure for two distinct warming scenarios of 1 °C/100 year and 3 °C/100 year using similar initial conditions (slope geometry, ocean bottom temperature, salinity, geothermal gradient) along with a uniform hydrate saturation of 3 % and sediment permeability of 10^{-15} m^2.

43.2.2 Soil Properties

Limited data exists for the mechanical properties of soils within the Arctic margin, especially for hydrate-bearing sediments. In our analyses soil properties (highlighted in Table 43.1) were based on results from core samples obtained during the National Gas Hydrate Program expedition offshore India (NGHP1, Collett et al. 2008), where hydrate veins were observed in fine-grained marine sediments.

For the undrained analyses different values of s_u were assigned to the three soil layers highlighted in Table 43.1. For the 5 m hydrate-free soil layer the assigned s_u value was based on the results of shear vane tests on near surface sediments with no hydrate present (Winters 2011). The value of s_u for the soil subject to hydrate dissociation was based on the results of Priest et al. (2014) who undertook

Table 43.1 Material properties for the different soils applied during drained and undrained analyses

Soil layer	Undrained s_u	Drained ϕ' and c
Hydrate-free	6 kPa + 0.8 kPa/m[a]	21°, 7.9 kPa[a]
Hydrate-bearing	50 kpa	30°, 50 kPa
Hydrate dissociation	6 kpa[b]	21°, 7.9 kPa[a]

[a]Winters (2011)
[b]Priest et al. (2014)

undrained triaxial tests on samples obtained from hydrate-bearing cores recovered during HGHP1. In these tests the hydrate veins were removed prior to testing such that the host sediment strength was tested at its original in-situ water contents. The value of s_u assigned to the hydrate-bearing layer (this layer has minor influence on slope stability) was notionally chosen to be greater than those for the hydrate-free layer. For the drained analyses a Mohr-Coulomb failure criterion was adopted and so relevant soil properties (friction angle, ϕ' and cohesion, c) were based on the results of drained triaxial tests at different effective stresses conducted on recovered samples from NGHP1 expedition (Winters 2011). As for the undrained analyses, values for the hydrate-bearing layer were notionally chosen to be greater than those for the hydrate-free layer.

A contrast in soil strength will occur at the base of the HSZ during dissociation and so the failure surface was prescribed along this interface, similar to that proposed by McIver (1982). All soils were assigned a saturated unit weight of 16 kN/m^3 relating to a porosity of 60 %, typical values for the near surface sediments recovered during the NGHP1 expedition (Collett et al. 2008).

43.3 Results and Discussion

43.3.1 Slope Stability Using Drained Soil Properties

Initial slope modeling conducted using a drained analysis with all soils parameters set to $s_u = 6$ kPa + 0.8 kPa/m (no hydrate throughout the slope) showed that for a 3° slope the factor of safety (FOS) for the critical slip surface was 3.4. In order for the soil to experience instability without hydrates (i.e. a FOS <1) a slope angle of at least 11° would be required for the applied soil properties. Figure 43.2 shows the calculated FOS for the different warming scenarios (see Fig. 43.1) using the undrained parameters highlighted in Table 43.1. For a 1 °C/100 year warming event the slope fails after 200 years, while for the 3 °C/100 year warming event the slope fails after 100 years. Figure 43.3 highlights the extent of the slope failure and the calculated FOS for the two separate analyses. The critical slip surface for event occurs at the base of the hydrate stability zone, where the weakened soil (due to hydrate dissociation) is in contrast with the stiffer underlying soils. The extent of the critical slip surface for the 3 °C/100 year case extends over 1500 m downslope, resulting in a sliding volume per meter across the slope ~35 × 10^3 m^3.

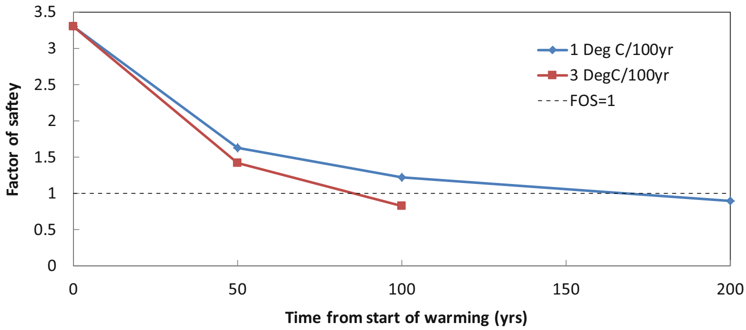

Fig. 43.2 Factor of safety resulting from hydrate dissociation with time due to increases in ocean bottom temperatures

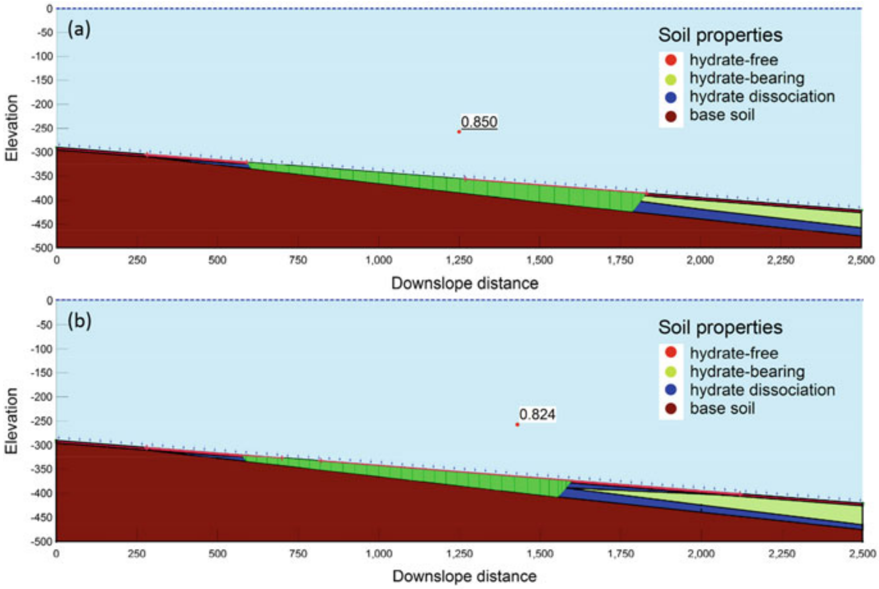

Fig. 43.3 Factor of safety and extent of failure surface resulting from hydrate dissociation due to (**a**) 1 °C/100 year temperature rise in ocean bottom temperatures after 200 year, and (**b**) 3 °C/100 year temperature rise in ocean bottom temperatures after 100 year

In the above analyses a constant s_u is assigned to the soil subject to hydrate dissociation. In reality, if the hydrate veins support the overburden stress then as the dissociation front advances downslope with time (predominantly at the base of the HSZ) the soil will gradually experience an increase in apparent overburden stress leading to consolidation of the soil, thereby increasing s_u. The degree of consolidation, and therefore the potential increase in s_u, will be highly dependent on the resultant soil properties such as; soil permeability, compressibility, drainage path,

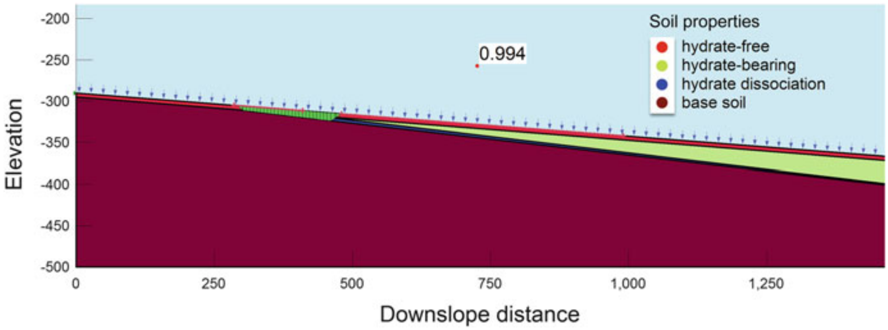

Fig. 43.4 Critical slip surface from drained slope stability analysis for 1 °C/100 year warming over 50 years due to 50 kPa pore pressure increase in hydrate dissociation zone (*colored blue*)

etc. Hydrate dissociation is greatest at the base of the HSZ and so the drainage path for fluid flow increases as the dissociation front moves downslope with time. For the 3 °C/100 year warming event and considering an average coefficient of consolidation, c_v, of 2.2×10^{-8} m^2/s (Winters 2011), which is a function of soil permeability and compressibility, the soil at the base of the HSZ at ~1500 m downslope would experience only ~26 % consolidation after 100 years from the onset of hydrate dissociation. This would suggest that the soil at this depth is likely to remain substantially undrained and exhibit a low s_u.

43.3.2 Slope Stability Using Drained Soil Properties

In addition to the reduction in s_u due to hydrate dissociation, an increase in pore pressure within the sediment can occur due to the release of methane gas. This will lead to a reduction in effective stress, leading to shear failure of the soil. To consider the influence of excess pore pressure on slope stability drained analyses were conducted with increasing pore pressure applied to the region subjected to hydrate dissociation using the drained soil parameters summarized in Table 43.1. Results show (Fig. 43.4) that shallow, near surface, localized failures (extending 100–200 m downslope) with a FOS <1 occur when the excess pore pressure within the soil was >50 kPa.

It has been shown experimentally that during dissociation (for a 5 % hydrate saturation) the rise in pore pressure for an undrained sand sample can be as great as ~170 kPa (Wu and Grozic 2008). The actual increase in pore pressure within sediments on the continental margins during hydrate dissociation over time will depend on the fully-coupled relationship between fluid flow, heat flow, hydrate dissociation and sediment strength/stiffness. Considering similar slope geometry to that modeled, Thatcher et al. (2013) showed for a sediment with a permeability of 10^{-16} m^2 (typical for Arctic sediments), 5 % hydrate saturation and a geothermal gradient of 0.65 °C/m that pore pressure is likely to exceed lithostatic pressures within 25 years for ~3 °C/100 year temperature increase. However, they also showed that an increase in effective permeability of the sediment due to the formation of cracks, either from the hydrate veins or from overpressure, was required to match the time required for gas expulsion at the seafloor to match observations, thus limiting the magnitude of any pore pressure increase. Therefore, localized slope failures due to the generation of excess pore pressures may occur in the short term, depending on actual permeability of the sediment. These localized failures may cause increased loading on soils downslope leading to progressive failure of the slope as a whole, involving both undrained and drained behavior.

43.4 Conclusions

Warming of the Arctic Ocean, through ongoing climate change, is likely to lead to the dissociation of gas hydrate that resides within the sediment on its upper continental slopes. In fine-grained sediments, where the hydrate exists as fracture-filled veins, this will lead to a reduction in soil strength as well as an increase in pore pressure through release of methane gas. Modeling dissociation using a reduction in undrained shear strength indicates large-volume slope failures could occur after some time, when a sufficient mass of sediment has undergone strength reduction. In contrast, drained analyses, where increases in pore pressures as a result of hydrate dissociation were considered, gave rise to shallow localized slope failures at much earlier times than the undrained cases. These shallow failures may progress down-slope due to increased loading (from the failing mass above) and ongoing hydrate dissociation.

The ‘factors of safety’ for slope failures were computed at discrete time steps with a number of simplifying assumptions with regard to soil behavior during dissociation (drained and undrained) and the assumption of an idealized slip surface at the base of HSZ. In reality, during hydrate dissociation, the soil is likely to be neither fully drained nor undrained, with the relationship between the two idealized behaviors being highly dependent on the effective permeability of the soil. This will lead to changes in variations in soil properties with time throughout the slope that was not accounted for in our analyses. In addition, it is implicitly implied that the lateral distribution of hydrate throughout the slope was uniform, which for fine-grained sediments may not be valid. Given that observed submarine slope failures on continental margins do not seem to exhibit large-scale slide plane type failures suggest that the modes of failure due to hydrate dissociation are likely to be more complex than we have modeled.

To correctly assess the influence of hydrate dissociation on slope stability, resulting from climate change in the Arctic Ocean, will requires more detailed characterization of soil properties relevant to the Arctic and the likely changes that may occur during hydrate dissociation, including effective permeability. In addition, more complex analyses, taking account of discrete changes in soil properties, are required to capture realistic failure modes.

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References

Archer D, Buffet B, Brodkin V (2009) Ocean methane hydrates as a slow tipping point in the global carbon cycle. Proc Natl Acad Sci U S A 106(49):20596–20601

Biastoch A, Treude T, Rüpke LH et al (2011) Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification. Geophys Res Lett 38:L08602. doi:10.1029/2011GL047222

Collett TS et al (2008) National gas hydrate program expedition 01 initial report, Dir. Gen. of Hydrocarbons, Minist. of Pet. and Nat. Gas, New Delhi

Council of Canadian Academies (CCA) (2008) Energy from gas hydrates: assessing the opportunities & challenges for Canada. Report of the expert panel on gas hydrates. J Grace (chair), Ottawa, Canada

Grozic JLH (2009) Interplay between gas hydrates and submarine slope failure. In: Mosher DC, Shipp RC, Moscardilli L et al (eds) Submarine mass movements and their consequences IV. Springer, Dordrecht, pp 11–30

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007: the physical science basis. Cambridge University Press, New York

Kim HS, Cho GC, Lee JY, Kim SJ (2013) Geotechnical and geophysical properties of deep marine fine-grained sediments recovered during the second Ulleung Basin Gas Hydrate expedition, East Sea, Korea. Mar Pet Geol 47:55–65

Kvenvolden KA, Lorenson TD (2001) A global inventory of natural gas hydrate occurrence. In: Paull CK, Dillon WP (eds) Natural gas hydrates: occurrence, distribution, and detection, Geophys. monogr. ser, vol 124. AGU, Washington, DC, pp 3–18

McIver RD (1982) Role of naturally occurring gas hydrates in sediment transport. AAPG Bull 66:789–792

Mienert J, Vanneste M, Bunz S et al (2005) Ocean warming and gas hydrate stability on the mid-Norwegian margin at the Storegga Slide. Mar Pet Geol 22:233–244

Paull C, Dallimore SR, Hughe-Clarke J et al (2011) Tracking the decomposition of submarine permafrost and gas hydrate under the shelf and slope of the Beaufort Sea. Paper presented at 7th International conference on gas hydrates, Edinburgh

Phrampus BJ, Hornbach MJ, Ruppel CD, Hart PE (2014) Widespread gas hydrate instability on the upper U.S. Beaufort margin. J Geophys Res Solid Earth 119:8594–8609. doi:10.1002/2014JB011290

Priest JA, Clayton CRI, Rees EVL (2014) Potential impact of gas hydrate and its dissociation on the strength of host sediment in the Krishna-Godavari Basin. Mar Pet Geol 58:187–198

Reagan MT, Moridis GJ, Elliott SM, Maltrud M (2011) Contribution of oceanic gas hydrate dissociation to the formation of Arctic Ocean methane plumes. J Geophys Res 116, C09014. doi:10.1029/2011JC007189

Rees EVL, Priest JA, Clayton CRI (2011) The structure of methane gas hydrate bearing sediments from the Krishna–Godavari Basin as seen from Micro-CT scanning. Mar Pet Geol 28(7): 1283–1293

Ruppel C (2011) Methane hydrates and contemporary climate change. Nat Educ Knowl 3(10):29

Sloan ED, Koh CA (2008) Clathrate hydrates of natural gases, 3rd edn. Taylor & Francis/CRC Press, Boca Raton

Sultan N, Cochonat P, Foucher JP, Mienert J (2004) Effect of gas hydrate melting on seafloor slope stability. Mar Geol 231:379–401

Thatcher KE, Westbrook GK, Sarkar S et al (2013) Methane release from warming-induced hydrate dissociation in the West Svalbard continental margin: timing, rates, and geological controls. J Geophys Res Solid Earth 118:22–38

Westbrook GK, Thatcher KE, Rohling EJ et al (2009) Escape of methane gas from the seabed along the West Spitsbergen continental margin. Geophys Res Lett 36(15):L15608

Winters WJ (2011) Physical and geotechnical properties of gas-hydrate-bearing sediment from offshore India and the northern Cascadia margin compared to other hydrate reservoirs. Paper presented at 7th International conference on gas hydrates, Edinburgh

Wu L, Grozic JLH (2008) Laboratory analysis of carbon dioxide hydrate-bearing sands. J Geotech Geoenviron Eng 134(4):547–550

Yun TS, Fratta D, Santamarina JC (2010) Hydrate-bearing sediments from the Krishna-Godavari Basin: physical characterization, pressure core testing, and scaled production monitoring. Energy Fuels 24:5972–5983. doi:10.1021/ef100821t