



# Shear strength of frozen sand with dissociating pore methane hydrate: An experimental study



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## ABSTRACT

This paper presents experimental results for peak shear strength of frozen sand containing methane hydrates within the pore space under dissociation at atmospheric pressure. During the experiments, the samples retained metastable pore methane hydrate due to the self-preservation effect. The tested samples were subjected to short-term uniaxial compression at temperatures from  $-1.8$  to  $-6.5$  °C. The gas hydrate component turned out to considerably affect the strength of the host frozen soil: the shear strength of frozen sediments decreased as saturation with metastable gas hydrate became lower. There is some critical hydrate saturation value ( $\sim 30\%$ ) below, which no further strength reduction occurs. Cyclic thawing-freezing increases considerably the strength of frozen samples that contain relict hydrates, primarily because denser ice, with fewer structural defects, forms by freeze back instead of molten porous hydrate-bearing ice. The obtained results indicate that geomechanical properties of frozen sediments correlate with the contents of relict gas hydrate and can be used for detection of hydrate-bearing permafrost layers.

## 1. Introduction

The first evidence that natural gas hydrates may exist in permafrost appeared almost fifty years ago, but they still remain poorly investigated (Chersky and Makogon, 1970; Max, 2000). The reason is primarily that gas hydrates are similar to pore ice in physical properties (Sloan and Koh, 2008), and their responses are hard to discriminate by conventional geophysical (mainly seismic) studies.

The presence of gas hydrates in shallow permafrost within 150 m has been inferred from field data and some implicit indicators (Dallimore and Collett, 1995; Dallimore et al., 1996). Methane gas hydrates may exist in the metastable zone (Chuvilin et al., 2000; Yakushev and Chuvilin, 2000) of frozen sediments above the zone of hydrate stability. They are remnant gas hydrates that formed earlier in frozen sediments under more favorable thermobaric conditions, became metastable in the course of later paleoclimatic events and permafrost evolution, and have survived due to the effect of self-preservation at negative temperatures (Ershov et al., 1991; Stern et al., 2001). The relict gas hydrate may be responsible for methane emission and gas explosion hazard in shallow permafrost during drilling and production in gas fields of northern West Siberia. The metastable gas hydrate

formations are extremely sensitive to various influences, including the anthropogenic impact and, in their turn, affect the physical properties of frozen sediments (Bukhanov et al., 2008). Permafrost gas hydrate creates serious geologic hazard and poses risks to oil and gas exploration and development and requires special studies. The physical (especially, mechanical) properties of frozen sediments with self-preserved pore gas hydrate can be investigated in experiments, with implications for geotechnical prediction and monitoring.

## 2. Mechanical properties of hydrate-bearing soil

The first experimental data on mechanical properties of clathrate-bearing porous media were obtained in the latest 1980s through uniaxial compression tests with fine quartz sand containing tetrahydrofuran (THF) hydrate (Parameswaran et al., 1989). In the low strain rate region, the compressive strength of the samples with THF was higher than that of frozen sand containing ice (Parameswaran et al., 1989), and similar results were reported in many later publications (Cameron et al., 1990; Yun et al., 2007; Lee et al., 2010; Smith et al., 2016). However, the data on strength and strain of THF-bearing sedimentary samples are poorly applicable to characterization of soils

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**Table 1**  
Sediment properties.

Type of sediment	Grain size distribution, %			Mineralogy, %	Salinity, %
	1–0.05 mm	0.05–0.001 mm	< 0.001 mm		
Fine sand	94.8	3.1	2.1	Quartz > 90	0.01

containing CH<sub>4</sub> or CO<sub>2</sub> hydrates, which have different structure and properties. In this context, THF hydrates can be used only for qualitative analysis of clathrate structures without special equipment necessary for investigation of natural gas hydrates.

L. Stern (Stern et al., 1996; Durham et al., 2003) was the first to study the mechanical properties of gas hydrates under equilibrium P-T conditions in triaxial tests and found out that pure methane hydrate could be 20 times or more stronger than ice at 140–200 K. Natural hydrate-bearing cores sampled beneath permafrost from well Malik 2L-38 (Mackenzie delta, Canada) showed much higher strength in the unfrozen state than their water-saturated counterparts (Winters et al., 1999, 2004, 2007). The strength was higher because pore hydrate cemented mineral particles and formed a hard mineral-hydrate frame. Experiments with natural hydrate-saturated cores from bottom sediments in the Nankai Trough (Japan) and artificial hydrate-bearing samples showed the strength to vary slightly in sediments with 20–30% hydrate saturation but to become 25–30% higher as the saturation increased to 50–60% (Masui et al., 2007; Miyazaki et al., 2011; Hyodo et al., 2013). The strength of hydrate-bearing sediments also depends on the hydrate former composition (Luo et al., 2013; Li et al., 2016): it is 10–15% higher in sediments containing CO<sub>2</sub> hydrate than in those with CH<sub>4</sub> hydrate.

Ever more reports on experimental studies of strength and strain in hydrate-saturated porous media have been appearing in recent years (Song et al., 2010; Li et al., 2012; Zhang et al., 2012; Pinkert and Grozic, 2014). Most often such experiments are carried out at low positive temperatures (between +2 and +10 °C) on model natural or artificial porous samples applying triaxial compression at a constant strain rate. The main aim is to obtain empirical relationships of strength, cohesion and friction angle with gas hydrate contents. Other experiments investigate the influence of gas hydrate dissociation at temperatures above 0 °C on the strength of hydrate-bearing sediments (Waite et al., 2008; Hyodo et al., 2013; Li et al., 2016). Dissociation of pore gas hydrates upon warming turns out to cause significant strength reduction (several times). If temperature and pressure changes cause only partial hydrate decomposition, the equilibrium gas pressure may recover, and the strength of the porous medium in this case will depend on the residual hydrate content. The strength reduction in sediment samples exposed to partial decomposition of pore methane hydrate does not exceed 30–40% in most experiments (Waite et al., 2008). Inasmuch as the experiments were mostly conducted at positive temperatures, the effect of cooling on dissociation of pore hydrates remained overlooked. Meanwhile it may lead to freezing of hydrate-bearing samples at low positive temperatures, which may bring errors to simulation of hydrate reservoir evolution during methane recovery.

Currently, there are few publications available on mechanical properties of hydrate-saturated sediments at temperatures below 0 °C. The first study of this kind belongs to Ershov et al. (1996) who noted that a frozen hydrate-bearing sand sample was stronger than a frozen hydrate-free analog. The tests were run at –6 °C and atmospheric pressure, under conditions of methane hydrate self-preservation (Ershov et al., 1996). Li et al. (2016) studied changes of strength and strain in artificial ice and hydrate-bearing clay sediments during depressurization and thawing. They observed higher values of the mechanical parameters at gas pressure above equilibrium than that below equilibrium (self-preserved hydrate) and 2–2.5-fold strength reduction upon thawing of hydrate-bearing samples. The studies, however, had a

drawback in preparation of frozen hydrate-bearing samples by pressing cooled dry kaolinite clay with crushed ice which converted to hydrate at negative temperatures. It can provide an overall homogeneous structure of samples but such samples poorly represent natural processes of hydrate formation in sediments.

Today the mechanical properties of hydrate-saturated sediments remain poorly investigated, and there is little experimental evidence for such sediments in the frozen state. These data can be useful for the evolution of low-temperature gas hydrate deposits and are extremely necessary for reliable physical modeling and numerical simulation, especially for evolving subpermafrost and intrapermafrost gas hydrate reservoirs and for wellbore stability (Freij-Ayoub et al., 2007). The required knowledge can be gained through special geomechanical testing of frozen sediments under the conditions that maintain self-preservation of pore gas hydrates.

### 3. Method

Sediment samples for experimental investigation of short-term strength of frozen hydrate-bearing sediments at temperatures below 0 °C were prepared using fine sand (Table 1) and 99.98% pure methane as the hydrate former. The gas was stored in a gas cell at a pressure of ~8–10 MPa. Water-saturated sediment samples were prepared with a specified initial moisture content (W, %) about 18 wt% and placed into a pressure vessel, which was then sealed, vacuumed, cooled and filled with the hydrate-forming methane gas creating the conditions for pore hydrate formation in the samples (Chuvilin et al., 2011). Hydrate formation started at temperatures below 0 °C (about –4 to –6 °C). In our case, gas hydrate was growing directly on pore ice, which inhibited moisture migration and ensured uniform distribution of gas hydrate in the samples. Then the temperature was raised gradually to low positive (+1 to +3 °C) values. The formation of pore hydrate accelerated as ice melted producing additional gas-water contacts. When hydrate formation stopped, the pressure vessel with hydrate-bearing sediments was cooled down to –6 ± 1 °C, whereby residual pore water not converted to hydrate froze up. Hydrate saturation in these obtained sediment samples reached 60% or more.

After formation the methane pressure in the vessel (at a temperature below 0 °C) was reduced to the atmospheric level (0.1 MPa) and the frozen hydrate-bearing sediments were taken out. The formed frozen pore gas hydrates remained stable at temperature about –6 ± 1 °C for a long time due to self-preservation at negative temperatures (Ershov et al., 1991; Stern et al., 2001). Thus it was possible to study their moisture content (W, wt%), density ( $\rho$ , g/cm<sup>3</sup>), porosity ( $n$ , u.f.), gas content, and mechanical properties. The gas content was estimated by measuring the amount of gas released during thawing of the sample placed in a saturated NaCl solution. The obtained parameter values were used to estimate hydrate saturation (Chuvilin and Kozlova, 2005; Bukhanov et al., 2008), assuming a hydrate number of 5.9 for methane hydrate:

- Volumetric hydrate content ( $H_v$ , %) is

$$H_v = \frac{V_h}{V_{sam}} \cdot 100\% \quad (1)$$

where  $V_h$  is the volume of methane hydrate,  $V_{sam}$  is the sample volume.

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