



# Strength behavior of methane hydrate bearing sand in undrained triaxial testing



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## ABSTRACT

Gas hydrates represent a potential future energy source as well as a considerable geohazard. In order to assess both the benefits and risks that gas hydrate bearing sediments pose, fundamental information about their physical properties is required. In this study, the undrained shear strength of methane hydrate bearing sand was investigated. The experimental program required modifications to an existing triaxial apparatus and accurate determination of the hydrate saturation lead to the use of two methods for comparison of the saturation calculations. Strength results indicated that the presence of gas hydrate will increase the sediment's undrained shear strength and corresponding stiffness. The relative contribution of cohesion and friction angle was observed to be a function of the hydrate saturation, for this particular hydrate formation methodology.

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## 1. Introduction

Methane hydrate represents an important possible future energy resource, provided the gas can be extracted and processed while meeting environmental standards and economic viability. Some estimates tout gas hydrates could potentially meet global energy needs for the next 1000 years (Demirbas, 2010). However, any perturbation to the thermodynamic equilibrium may push the methane hydrate bearing sediments out of the stability zone (high pressure, low temperature), thus inducing hydrate dissociation, loss of cementation, and a corresponding pore pressure increase. This, in turn, can cause wellbore failure and loss of platform foundations during gas extraction/production operations or, on a large scale, submarine landslides (Bryn et al., 2005; Carpenter, 1981; Crutchley et al., 2007; Field and Barber, 1993; Kvalstad et al., 2005; Mienert et al., 2005; Nixon and Grozic, 2007; Popenoe et al., 1993; Sultan et al., 2004a, 2004b; Vogt and Jung, 2002). Understanding the geomechanical properties of these sediments, particularly shear strength characteristics, is essential for stability analysis under different environmental conditions, whether natural or anthropogenic.

Laboratory determination of the shear strength of hydrate bearing sediments using the triaxial apparatus is complicated, due

to the high pressure, low temperature requirements, along with complexities in forming uniformly distributed hydrate. Depending on the hydrate formation method, pore pressure is provided through pressurized water or methane gas. Precise automatic operating systems are required to control and maintain pressure levels; this is particularly crucial during hydrate formation because the gas is continuously being consumed. High-pressure cylinder regulators cannot adequately control for pressure and temperature changes, where even small daily temperature fluctuations will alter water and gas pressures.

This paper describes a triaxial testing methodology for methane hydrate bearing samples, including calculation of hydrate saturation content. Using the methodologies described in the paper, the strength of intact methane hydrate bearing sands was investigated and these results are presented and discussed.

## 2. Laboratory hydrate formation techniques

Natural hydrate-bearing samples are difficult and expensive to acquire, and many complications remain in transferring preserved samples to testing apparatus in the laboratory (Rees et al., 2011). Thus, different laboratory methods have been developed to form methane hydrates in reconstituted sediments.

The most time-consuming and laborious method is the dissolved gas method, in which the hydrate is formed from a dissolved gas in the absence of free gas (Waite et al., 2009). This method is

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thought to most closely simulate the natural formation process in both arctic and deep coarse-grained seabed sediments (Buffett and Zatsepina, 2000; Spangenberg et al., 2005; Waite et al., 2011). Hydrate formation is induced by circulating water saturated with methane gas through the sediment, within the hydrate stability zone controlling both pressure and temperature. Hydrate growth rate is limited by the concentration of dissolved gas in the water; therefore, the formation time is long owing to methane's low solubility in water. Buffett and Zatsepina (2000) successfully used an aqueous solution with dissolved carbon dioxide (CO<sub>2</sub>) as the hydrate-forming gas in their experiments; these were the first experiments to show that hydrate formation in porous media under realistic conditions is possible in the absence of free gas. Carbon dioxide was used in this experiment because of the constraints of the high-required pressure and very low solubility of methane in water. Spangenberg et al. (2005) was the first to report the formation of hydrate with dissolved methane gas solution. The main goal of this study was to provide data necessary to prove theoretical models and calibrate interpretation methods that relate the hydrate content to physical properties such as seismic velocities and electrical resistivity. Using a glass bead pack, they saturated ~95% of the pore spaces with hydrate formed from dissolved-phase methane in ~50 days by pumping methane charged water via a gas/water chamber into the sample. The results supported their hypothesis that formations containing large volumes of pore filling hydrate can be obtained from upward migrating fluids that transport dissolved methane into the hydrate stability field. This study however did not investigate the shear strength characteristics of hydrate bearing sediments. Hydrate nucleation from the dissolved methane solution can be promoted by using surfactants (Zhong and Rogers, 2000) or flowing fluid through hydrate granules (Waite et al., 2008). These conditions add complications to the testing equipment and procedures, and the effects of surfactants on sediment strength are unknown.

Another hydrate formation method, referred to as partial water saturation, can reduce the nucleation time substantially by flushing pressurized methane gas through partially saturated sediment and cooling it into the stability field (Priest et al., 2005; Handa and Stupin, 1992; Waite et al., 2004). Alternatively, the method can be applied by injecting a known quantity of methane as free gas and then flooding with water (Priest et al., 2009; Winters et al., 2000, 2002). An important drawback of the partial water saturation methods is that both above approaches may lead to preferential hydrate formation at particle contacts causing cementation of the sediment skeleton or frame supporting. These growth habits may be quite different from the pattern of many naturally occurring hydrates (Ebinuma et al., 2005; Kneafsey et al., 2007; Masui et al., 2005). Although near faults, or at the base of the hydrate stability zone, hydrate formation may take place in the presence of abundant free gas and a gas-rich formation methodology may be a better natural analog (Waite et al., 2009; Priest et al., 2005).

Hydrate formation from ice seeding (Priest et al., 2005; Stern et al., 1996) or hydrate premixing (Hyodo et al., 2005) mixes soil grains with ice or methane hydrate granules, respectively. The mixture is then pressurized into the hydrate stability field with excess methane gas. Existing ice or hydrate lattice facilitates hydrate nucleation under controlled melting. Priest et al. (2009) showed the distribution of ice seeded hydrate was not different than hydrate formed from partial saturation techniques. The sequence of events in these techniques however deviates from that in natural systems, as do all laboratory formation methodologies; however, concerns remain about the soil structure and if individual particles have been separated by the ice nodules (Yun et al., 2007).

Each of the methods for forming hydrate produces different methane growth patterns, resulting in different macro-scale behavior of seemingly identical sediments, particularly affected are the mechanical properties of sediments (Waite et al., 2009; Priest et al., 2009).

### 3. Strength of hydrate bearing sands

Knowledge of the strength behavior of hydrate bearing sediments is crucial for predicting reservoir response during production and the potential for geohazards, particularly submarine sliding (Grozic, 2010). Because of the complex nature of hydrate sediment interactions, strength testing on intact core is difficult. Hydrate redistribution and fabric disturbance may occur during pressure release (even with pressure cores, the in situ pressures must be released momentarily to transfer the core into the triaxial apparatus), thus only a limited number of strength tests have been performed on samples containing natural hydrate recovered from drilled wells.

The strength of intact pure hydrate can be 20 times that of pure ice, a contrast that increases at lower temperatures (Durham et al., 2003). When contained within sediments, laboratory results show an increase in strength of hydrate bearing sediments over hydrate free sediments (Ebinuma et al., 2005; Masui et al., 2005, 2008; Miyazaki et al., 2011) with hydrate and ice bearing sediments having similar strengths (Winters et al., 2004a). The strength of hydrate bearing sediments will be a function of the hydrate saturation, strain rate, temperature, consolidation stress, grain size, density, and cage occupancy (Winters et al., 2004a; Miyazaki et al., 2011).

Through an investigation of the undrained shear strength of laboratory formed specimens containing hydrates and other pore fillings, Winters et al. (2004b; 2007) noted an increase in strength for the hydrate specimens, which was directly related to hydrate saturation. Hydrate contained within the pore spaces accentuated the pore pressure response relative to that of a non-hydrate bearing sample; during shear the pore pressure decreased more in coarse grained sediments and increased more in fine grained sediments; the presence of a (free) gas phase dampened the pore pressure response (Winters et al., 2007). Similarly, testing of natural hydrate cores (coarse grained) from the Mallik 2L-38 well showed the shear strength of hydrate samples was higher than non hydrate bearing samples (Winters et al., 2004a).

Masui et al. (2005) and Miyazaki et al. (2011) investigated the effect of hydrate saturation on the drained strength of laboratory sand specimens formed from ice-sand mixtures and water-sand mixtures, prepared by freezing water-sand mixtures and then allowing them to thaw under pressure in the presence of methane. The specimens were water saturated prior to testing. A significant increase in shear strength and elastic modulus with increasing hydrate saturation was observed in their results. The formation of hydrate between the sand particles contributed to an increase in cohesion but had little impact on the friction angle (Masui et al., 2005; Suzuki et al., 2008). Testing to date indicates that stiffness, cohesion, and dilation increase with increasing hydrate saturations, while friction angle remains unaffected (Yoneda et al., 2007).

The laboratory technique used for hydrate formation has a strong affect on the shear strength. Strongly bonded laboratory formed partially saturated specimens exhibit marked increases in strength with increasing hydrate saturation, while weakly bonded hydrate specimens (i.e. ice seeding formation) only display an increase in strength at high hydrate saturations (Ebinuma et al., 2005). Priest et al. (2009) noted a significantly higher stiffness in excess-gas hydrate specimens when compared to their specimens formed using the excess-water hydrate formation technique. As the hydrate saturations become high, the effects of formation history begin to diminish (Waite et al., 2009).

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