Undrained shear strength of methane hydrate-bearing sand; preliminary laboratory results

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ABSTRACT
Methane hydrates are promising energy resources of natural gas that form at high pressure and low temperature in seafloor sediments and permafrost regions. In hydrate accumulations, understanding of the physical and mechanical properties of hydrate bearing sediments is practically important and also an essential input into accurate numerical simulations. An experimental program investigating the shear strength and volume change characteristics of gas hydrate bearing sand was undertaken using undrained triaxial testing. The results indicate strength of hydrate bearing sand is strongly related to how the hydrate has formed within the sediment.

RÉSUMÉ
Les hydrates de méthane sont des ressources prometteuses d'énergie. Ce sont des gaz naturels qui se forment à hautes pressions et basses températures dans les sédiments sous-marins et les régions de pergélisol. Dans les accumulations d'hydrates, la compréhension des propriétés physiques et mécaniques des sédiments contenant des hydrates est importante en pratique, mais est aussi essentielle pour effectuer des simulations numériques précises. Un programme expérimental s'intéressant à la résistance au cisaillement et aux caractéristiques des changements de volume des sables contenant des hydrates a été réalisé utilisant un test triaxial non-drainé. Les résultats indiquent que la résistance des sables contenant des hydrates est fortement liée à la façon dont les hydrates se sont formés dans les sédiments.

1 INTRODUCTION

Methane hydrates are promising energy resources of natural gas that form at high pressure and low temperature in seafloor sediments and permafrost regions. Efficient and economic gas extraction from these accumulations involves various technical challenges; thus numerical simulators are required to evaluate gas productivity scenarios. In hydrate accumulations, understanding of the physical and mechanical properties of hydrate bearing sediments is practically important and also an essential input into accurate numerical simulations.

Hydrates also pose a geohazard in our exploration for, and production of, conventional offshore hydrocarbon reserves; with hydrate dissociation being linked to submarine slides, gas blowouts, and near well failures. Environmental implications of hydrate deposits can be negative, with methane release to the atmosphere, or positive, with potential storage of carbon dioxide in hydrate form.

Gas hydrates are solid crystalline compounds comprising hydrogen-bonded water molecules forming a rigid crystal lattice stabilized by encaged gas molecules, predominately methane. Although our knowledge of the geomechanical properties of hydrate bearing sediments is immature, laboratory experiments, small scale physical modeling, and theoretical analyses demonstrate the presence of hydrate will increase strength and stiffness and decrease permeability; dissociation of the hydrate induces fluid and gas production, loss of strength and stiffness, and elevated pore pressures. The magnitude and quantification of these parameters is highly dependent on the mode of hydrate occurrence; whether in situ or laboratory formed.

This paper presents a review of our current knowledge base and some preliminary laboratory results on the strength of intact methane hydrate bearing sands.

2 STRENGTH OF HYDRATE BEARING SANDS

Knowledge of the strength behavior in hydrate bearing sediments is crucial for predicting reservoir response during production and the potential for submarine sliding and other geohazards. Because of the complex nature of hydrate sediment interactions, strength testing is difficult and time consuming, and only a limited number of strength tests have been performed on hydrate bearing samples.

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 (Masui et al. 2005, 2008; Ebinuma et al.

2005), 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). The mechanisms controlling the strength of hydrate bearing sediments are complex. Waite et al. (2009) based on the work of Yun et al. (2007) has presented a summary of hydrate saturation effects on the strength mechanisms, which is summarized in Figure 1.

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, which during shear decreased in course grained sediments and increased in fine grained sediments; the presence of a gas phase dampened the pore pressure response (Winters et al. 2007). Testing of natural hydrate core (coarse grained) from the Mallik 2L-38 well similarly showed the shear strength of hydrate samples was higher than non hydrate bearing samples (Winters et al. 2004a). Masui et al. (2005) investigated the effect of hydrate saturation on the strength of laboratory sand specimens formed from ice-sand mixtures and water-sand mixtures and noted a significant increase in shear strength and elastic modulus with increasing hydrate saturation. 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.

A temperature dependence on strength was noted in synthetic THF (tetrahydrofuran) hydrate bearing sands, with colder specimens having increases in strength (Cameron et al. 1990). Comparing THF hydrate bearing sands to ice bearing sands, Cameron et al. (1990) noted a greater increase in strength for ice bearing sands with decreasing temperatures and less time dependent strain (creep) in the THF hydrate samples. Hyodo et al. (2009) formed methane hydrates in partially saturated sand specimens to similarly conclude that specimen strength increased as temperature decreased and back pressure increased.

How the hydrate and sediment interact also affects bulk sediment strength. Strongly bonded laboratory formed “wet” specimens (pumping methane gas into saturated sand), exhibit marked increases in strength with increasing hydrate saturation, while weakly bonded hydrate specimens (i.e. ice seeding or gas-wet formation) only display an increase in strength at high hydrate saturations (Ebinuma et al. 2005). As the hydrate saturations become high, the effects of formation history begin to diminish (Waite et al. 2009).

Initial confining pressure, or consolidation stress, will have an impact at lower hydrate saturations, with lower confining pressure, hydrates exert a greater impact on the strength; however, as the hydrate saturation increases (greater than 50%), strength becomes somewhat

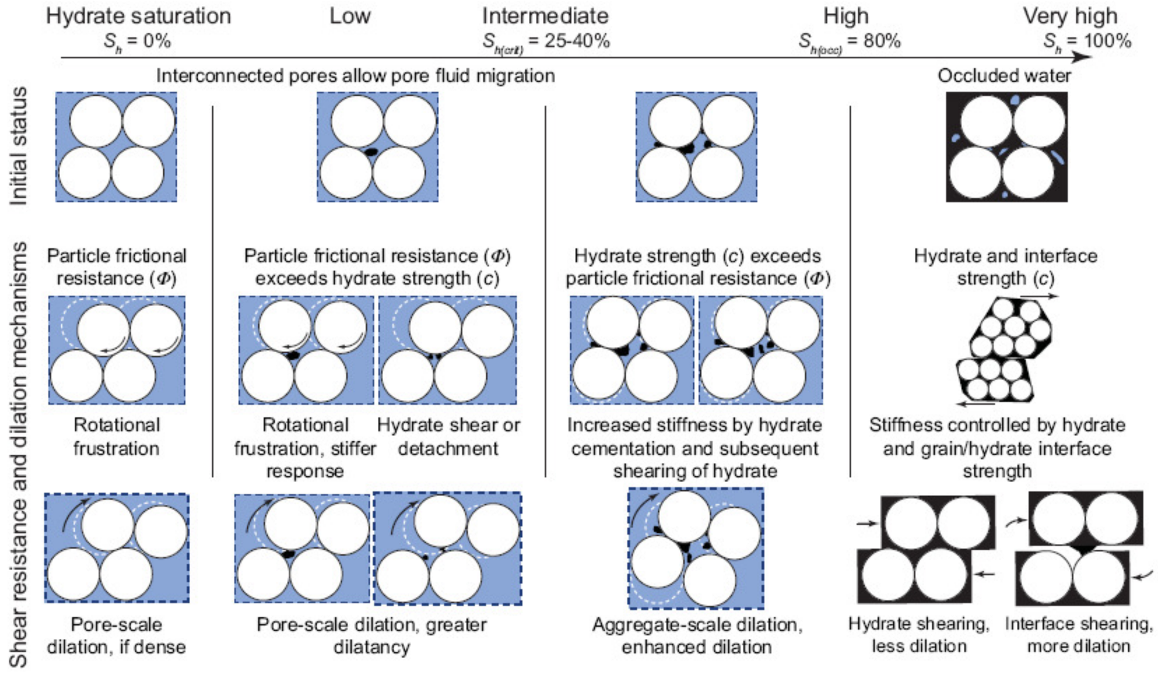

Figure 1. A summary of the mechanisms controlling the shear strength of hydrate bearing sediments, where soil grains are shown in white, hydrate in black, and water in blue (after Waite et al. 2009; modified from Yun et al. 2007). At high hydrate saturations effective stress becomes invalid and interpretations must be based on total stress.

independent of initial confining pressure (Yun et al. 2007). At these high hydrate saturations, the hydrate controls the strength and deformation characteristics such that initial effective stress looses relevance (Fig. 1; Waite et al. 2009).

2.1 Expressions to Estimate Strength

Using THF synthetic hydrates in sand, silt, and clay, with hydrate saturations of 0, 50%, or 100%, Yun et al. (2007) noted that in undrained triaxial strength testing, the stress strain curve indicated increasing secant stiffness, increasing deviator stress, and increasing brittleness with increasing hydrate saturation. Although an emphasis is placed on high hydrate contents (≥ 50%), Santamarina and Ruppel (2008) observed some commonalities in the strength data: 1) at low hydrate concentrations, the undrained shear strength is determined by the effective friction strength; 2) the contribution of hydrate strength increases non-linearly with increasing strength, becoming important at high hydrate saturations; and 3) the effect of hydrates is more pronounced at lower porosities. Combining these observations, lead to an expression to capture the undrained strength of their laboratory results:

$$S_u = a\sigma'_o + bq_n\left(\frac{S_h}{n}\right)^2 \qquad [1]$$

where S_u, is the undrained shear strength, σ'_o is the isotropic effective stress, q_n is the hydrate strength (assumed to be 8 MPa; Durham et al. 2005), S_h is the hydrate saturation, n is the porosity and a and b are fitting parameters. As Santamarina and Ruppel (2008) describe "the coefficient a captures friction and pore pressure generation in the sediment, while b is an indication of the hydrate's ability to contribute to the strength of the hydrate-bearing sediment. In other words, b is expected to reflect the formation method/habit of hydrate in a given soil." A good agreement between the measured and predicted strength values for their THF tests was observed using the following fitting parameters: sand (a=1.55, b=0.14), crushed silt (a=1.55, b=0.16), precipitated silt (a= 0.9, b=0.5), and kaolinite (a=0.5, b=0.07). In this expression, and indeed similar expressions developed for small strain stiffness, electrical conductivity, and permittivity, the S_h (which ranges from 0 to 1), is raised to a power greater than one, which indicates, in mathematical terms, the impact of hydrate on physical properties is reduced in sediments with low hydrate saturations (Santamarina and Ruppel 2008).

Natural marine sediments often contain less than 20% hydrate, hence further laboratory investigations at lower hydrate contents are required to confirm the expressions and findings.

Miyazaki et al. (2008) proposed a variable-compliance-type constitutive model for hydrate bearing sands, which was verified by triaxial testing on sands with hydrate saturation varying from 0% to 35% (Masuri et al. 2005). By curve fitting the results, the following expression for peak strength in constant strain triaxial shear testing was obtained:

$$\sigma_c = 3.67\sigma'_3{}^{0.754} + 0.00249S_h{}^{1.86} \qquad [2]$$

where σ_c is the peak strength, σ_3' is the effective confining pressure, and S_h is the hydrate saturation. Loading rate dependency was also investigated in this study by alternating strain rate during the testing, and the final constitutive model is able to capture the time-dependent properties of hydrate bearing sands; although more verification through further experimental studies is suggested (Miyazaki et al. 2008).

3 EXPERIMENTAL PROGRAM AND RESULTS

The experimental setup, including sample preparation, hydrate formation, and estimation of hydrate saturation is described in the companion paper in this proceedings (Ghiassian and Grozic 2010). In total five successful undrained triaxial strength tests were carried out using the University of Calgary's Geotechnical Gas Hydrate Research Laboratory. Of these tests, three were conducted on conventional water saturated Ottawa sand under three different effective confining pressures in undrained shear. The confining pressures tested were 250 kPa, 500 kPa, and 1000 kPa; only the results for the 1000 kPa test have been included in this paper. The other two triaxial tests contained gas hydrates, with one test formed using the partially saturated "gas wet" method and one using the dissolved gas method (see Ghiassian and Grozic 2010); hydrate saturations (pore occupancy) were approximately 70% and 60%, respectively. There is some uncertainty in hydrate saturation, as we recognized with continued testing that formation time will have an effect.

Table 1 summarizes the results of the tests to date. All tests showed strain hardening and dilation upon shear with pore pressures initially rising and then falling rapidly upon further strain. Figures 2 illustrates the stress strain curves for the three tests presented here; pore pressure versus strain is shown in Figure 3.

Table 1. Summary of test results.

Test	S_H	Formation Method	e_i	♬$_c$ (kPa)	♬$_c$' (kPa)	T (^oC)	p'$_{SS}$ (kPa)	q$_{SS}$ (kPa)	p'$_{max}$ (kPa)	q$_{max}$ (kPa)	c' (kPa)	♬' (^{o})	E_{sec} (kPa)
Sat	0	-	0.61	2000	1000	-	1484	1718	2702	3041	-	29.1	30766
H-PS	69%	PS	0.60	15000	1000	4.8	5864	13963	5864	13963	1963	42.8	55709
H-DG	60%	DG	0.60	15000	1000	4.7	1884	2115	4653	4862	-	28.4	41389

Notes: S_H – hydrate saturation (pore occupancy); e_i – initial void ratio; σ_c – confining pressure, σ'_c – effective confining pressure, T – temperature, p'_{ss} – mean normal effective stress at steady state, q_{ss} – deviator stress at steady state, p'_{max} – maximum mean normal effective stress, q_{max} – maximum deviator stress, c' – effective cohesion, ϕ' – effective friction angle, E_{sec} – secant modulus at failure, $p' = (\sigma_1'+2\sigma_3')/3$ and $q = \sigma_1' - \sigma_3'$

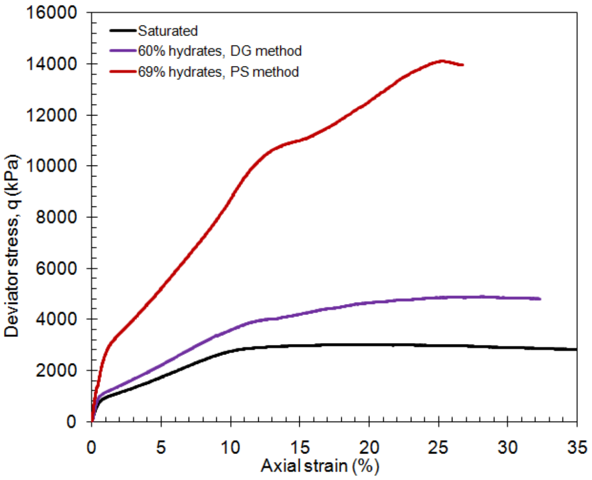

Figure 1. Deviator stress versus axial strain for three tests; Sat S_H=0%, DG S_H=60%, and PS S_H=69%.

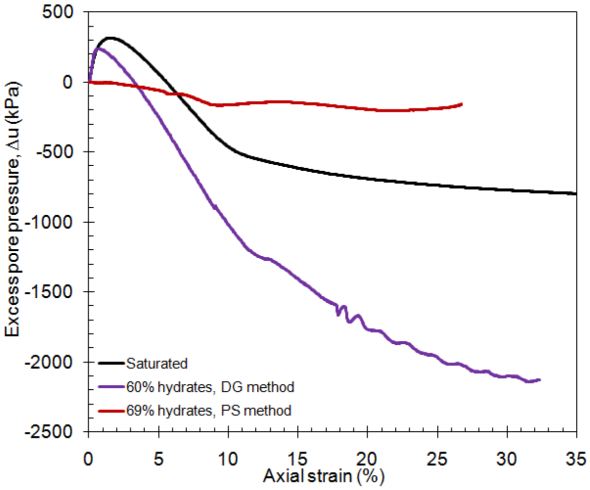

Figure 2. Excess pore pressure versus axial strain for three tests; Sat S_H=0%, DG S_H=60%, and PS S_H=69%.

In comparing the strength data for the three tests, the presence of hydrates clearly increases strength; however, the specimen with the dissolved gas shows only some strength increase relative to the un-hydrated specimen, while with not significantly more hydrates, the partially saturated specimen exhibits a marked strength increase. The clear differences in strength can be attributed to the hydrate mode of occurrence; using the dissolved gas method the hydrate is thought to form within the soil voids thus acting only as "extra particles" and thus no having a significant effect on the specimen response (although this will change if the hydrate content increases to the extent it fills the pores. The lack of cementing for dissolved gas specimens was also noted by Winters et al. (2004a).

From a comparison of Sat and H-PS, it is clear that gas hydrates can significantly increase the undrained shear strength. The undrained shear strength, c_u, defined as $q/2$, for Sat, H-PS (S_H = 69%), and H-DG (S_H = 60%), would be 1521 kPa, 6982 kPa, and 2431 kPa, respectively. This represents an increase in undrained shear strength of 4.6 to 1.6 times, which can be attributed to some hydrate cementation. Similarly, the secant modulus, E_{sec}, also increases with increasing hydrate content, again indicating that hydrates add to the soil stiffness.

The excess pore pressure response indicates all three samples exhibited a dilative behaviour. The dissolved gas specimen showed significantly enhanced dilation, which is consistent with Waite et al. (2009) and Yun et al. (2007) who proposed greater dilation at intermediate hydrate saturations.

The partially saturated specimen shows significantly less dilation, and in fact, little pore pressure response at all. This is most likely not a valid pore pressure response but a manifestation of experimental conditions. Although pore pressure was measured with an additional transducer placed as close to the specimen as possible (connect to the triaxial base in this case), there was obviously not full connectivity between the pore fluids and the pore pressure transducer because of the hydrate formation at the top and bottom of specimen. This "lack of result" is actually consistent with observations from other testing which indicates that the hydraulic conductivity of hydrate bearing sands decreases to virtually non-existent at hydrate saturations greater than approximately 60-65% (Ordonez et al. 2009). Thus, although presented here for interest, the pore pressure data for test H-PS should not be considered accurate. Future tests will involve embedding micro pressure-temperature recorders (about the size of a multi-vitamin) into the sand specimen during sample preparation. These recorders will provide a more realistic and accurate indication of the localized pressures and temperatures at two locations within the specimen.

The data for all three tests are compared in mean normal effective stress versus deviator stress (p' – q) plots in Figure 3. The slope of the critical state line for the saturated specimen (i.e. no hydrates), M, is estimated to be 1.17, which is consistent with previous research on Ottawa sand where M values of 1.12 (Sasitharan et al. 1994) and 1.15 (Skopek 1994) have been reported. The M value for the 60% hydrate specimen is estimated at 1.12, which is again consistent with previously reported values. Figure 4 illustrates a "zoom in" of the p'-q plot to highlight the similarities between the two tests, Sat and H-DG. The specimen containing 69% hydrates shows a markedly different behaviour and M is estimated to be 2.30. It will be very interesting to analyze further testing to determine if the difference in critical state behaviour is a function of the formation methodology or the lack of accurate pore pressure data.

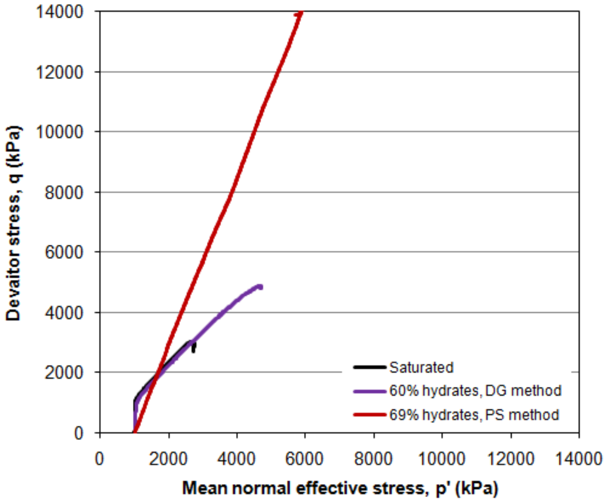

Figure 3. p'-q plots for all three tests.

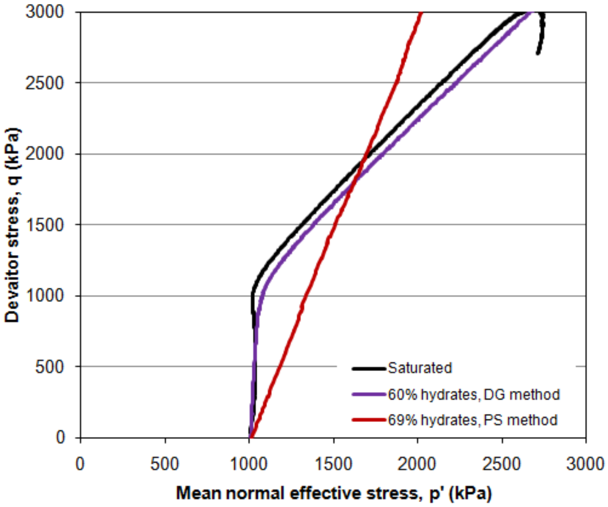

Figure 4. Closer view of p'-q plots illustrating the similarities between Sat and H-DG.

These preliminary indicate that the presence of gas hydrate has a strong influence of specimen strength, with the partially saturated specimen displaying high strength parameters and modulus. One distinct characteristic of this test is the presence of very high effective cohesion, estimated to be about 1963 kPa, which is attributed to hydrate cementation. This phenomenon is illustrated in Figure 5, as the large deviation of the failure line from the origin. Included in Figure 5 is a closer view of the determination of the failure envelope, which was estimated by passing a line through the data in the failure zone. The very high estimated friction angle (42.8^{o}), underlines the significant influence of hydrate formation habit on the strength behaviour. The partial water saturation methodology appears to lead to preferential hydrate formation at grain contacts and results in significant stiffening of the soil framework. Other investigators have noted or hypothesised a similar phenomenon (e.g. Chuvilin et al. 2003; Ebinuma et al. 2005; Klapproth et al. 2007; Kneafsey et al. 2007; Masui et al. 2005). A small amount of hydrate, when formed in the cementation habit, can dramatically increase the shear and bulk stiffness by bonding adjacent grains together (Dvorkin et al. 1999).

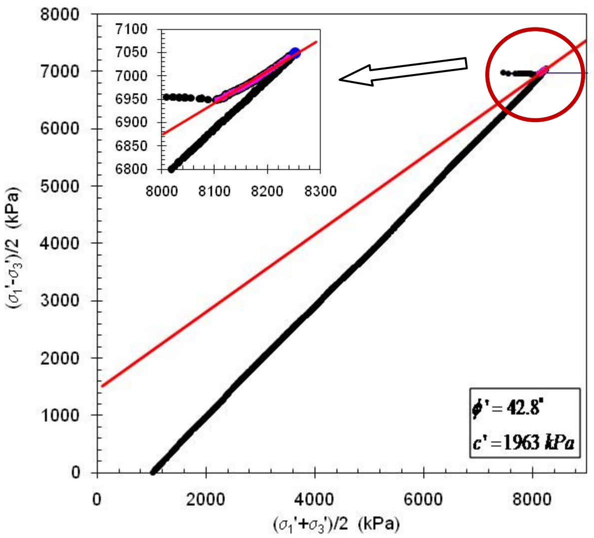

Figure 5. Analysis of cohesion and friction from H-PS containing 69% hydrates; inset is a closer view of the failure zone.

The shear characteristics of the dissolved gas specimen appear to be very different from the partially saturated specimen, again highlighting the effect of hydrate formation habit. First, no cohesion is obtained in the dissolved gas method, indicating that the dissolved gas method creates no important cementation between particles; this was also noted by Winters et al. (2004a). Second, the secant modulus is lower than H-PS, which is expected. The estimated friction angle also appears quite different, comparing 42.8^o obtained from H-PS to 28.4^o seen here in H-DG; a value similar to the non-hydrated plain sand specimen (29.3^o). Hydrate nucleation in the pores through the dissolved gas solution seems have a lubricating effect, rather than cementing, acting to decrease the effective friction angle; although the stiffness is somewhat increased. However, this trend may change at higher hydrate contents. More test results will add additional information on this subject.

4 DISCUSSION

4.1 Comparison to Predicted Strength

The expressions developed by Santamarina and Ruppel (2008) and Miyazeki et al. (2008) to capture the undrained strength of their laboratory results are plotted with the currently available laboratory data from this study (Figure 6). For the Santamarina and Ruppel (2008) expression, the fitting parameters (*a* and *b*) which they suggested for sand have been used in the model. It is quite interesting to note that the Santamarina and Ruppel model shows a good fit with the data from the non-hydrated and partially saturated specimen. The Miyazaki et al. Model doesn't fit the laboratory data quite as well. The dissolved gas specimen doesn't match up with either expression, which is a reflection of how very few dissolved gas laboratory tests have been conducted. In terms of the number of hydrate bearing strength tests (very low), the expressions from the published literature are in reasonable agreement and perhaps better agreement than expected, given the complexities and uncertainties of hydrate-bearing sediments testing.

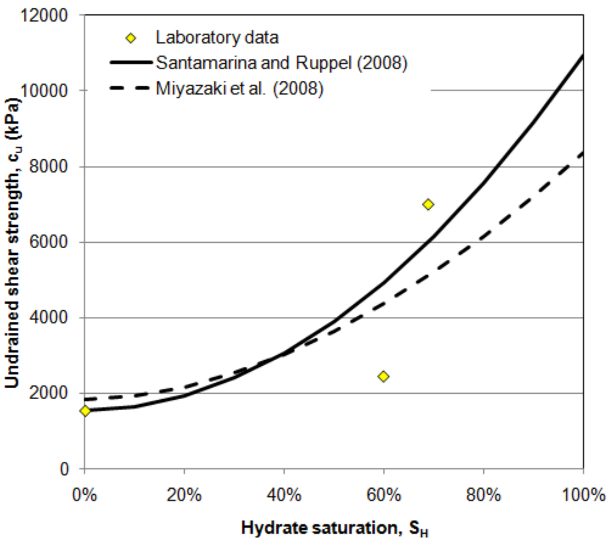

Figure 6. Comparison of laboratory results to models/expressions proposed in the literature.

4.2 Comparison of Test Results

Based on the analyses of these preliminary tests, it is clear that the presence of methane hydrates will increase soil stiffness and strength. It appears that the friction angle is not significantly affected at lower hydrate contents, which similar to saturated sand, exhibit no cohesion. As the hydrate content increases or the formation methodology changes, hydrate can cement the grains resulting in increased friction angle and apparent cohesion.

The hydrate formation methodology strongly influences how the gas hydrate exists within the soil specimen, which is referred to as the mode of occurrence. The mode of occurrence has an impact on the gas hydrate strength, yet exactly how large the impact of mode of occurrence is at similar hydrate contents has yet to be quantitatively determined.

5 FUTURE WORK

The work presented here comprises preliminary results from an ongoing testing program to comprehensively examine the strength of methane hydrate bearing sands. Future work includes further analysis of the effects of hydrate saturation, hydrate mode of occupancy (i.e. formation technique), effective confining pressure, and temperature on the undrained shear strength. This data set, once completed, will form a fundamental and not yet available foundation for analyzing the strength of methane hydrate accumulations.

6 CONCLUSIONS

The strength of methane hydrate bearing soils is a fundamental parameter required for assessment of methane gas production from hydrate accumulations and for assessment of submarine slope stability. Because of the complexities of gas hydrate testing, both in the laboratory and in situ, little strength data is currently available. This paper presented some preliminary results on what is to be a comprehensive program aimed at quantifying the impact of hydrate concentration and mode of occurrence on the undrained shear strength. The results to date indicate that the presence of hydrates will increase the soil stiffness and strength; however, the mode of failure, and strength gained is highly dependent upon the amount of hydrate in the specimen and the laboratory technique used to form the hydrate.

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