The Formation of Laboratory Analogues of Natural Hydrate-Bearing Fine-Grained Soil

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ABSTRACT

Gas hydrates form in deep-water marine sediments, and have been suggested as being a geohazard when temperature or pressure changes result in hydrate dissociation, with fine-grained hydrate-bearing sediments posing the greatest potential risk. Recent drilling expeditions with improved sampling techniques have revealed that within fine-grained soils, hydrates form complex, sub-vertical veins. These veins are hypothesized to lead to an increase in the strength and stiffness of the hydrate-bearing soil. However, current understanding of the strength and deformation behaviour of hydrate-bearing sediments is limited to laboratory studies in which hydrate is formed within the pore space of sediments. This paper presents a detailed procedure in which vertical, cylindrical synthetic hydrate veins are formed within a consolidated laboratory-mixed fine-grained soil, and are then isotropically reconsolidated within a triaxial cell. Results indicate that hydrate veins remain intact throughout this process.

RÉSUMÉ

Les hydrates de gaz se forment dans les sédiments des fonds marins. Les sédiments à grains fins qui renferment des hydrates peuvent poser un risque si des changements de température ou de pression provoquent la fonte des hydrates. Des expéditions de forage ont révélé que les hydrates forment des veines complexes et sub-verticales dans les sédiments à grains fins. L'hypothèse est que ces veines d'hydrates causent une augmentation de la résistance et de la rigidité du sédiment. Cependant, notre compréhension de la résistance et du comportemtent en déformation des sédiments contenant des hydrates est limitée à des études en laboratoire lors desquelles les hydrates se forment dans les pores du sédiment. Cet article présente une procédure détaillée pour former des veines synthétiques verticales et cylindriques d'hydrates dans un sédiment à grain fin. Les échantillons sont ensuite reconsolidés sous pression isotrope dans une cellule triaxiale. Les résultats indiquent que les veines d'hydrates restent intactes tout au long de la procédure.

1 INTRODUCTION

Gas hydrates are solid compounds stable under low-temperature, high-pressure conditions, occurring naturally within deepwater sediments along the world's outer continental margins and onshore beneath permafrost in Arctic regions. Strong global interest in this hydrocarbon deposit has been generated due to its potential as an unconventional gas resource, its theorized role in climate change and its impact as a geotechnical hazard.

Marine hydrates can pose a geohazard when bottom water temperatures and/or pressure conditions change to outside the pressure-temperature envelope at which they are stable, leading to hydrate dissociation. Dissociation involves the release of gas and water into the sediment pore space, several times larger in volume than its original form, resulting in excess pore pressure generation, ultimately leading to a reduction in soil strength and volumetric deformation. Pressure and temperature changes in soil conditions occur due to human activity on the sea floor (e.g. pipeline installation, drilling-related production) and changes in environmental conditions (e.g. long-term sea level and temperature changes).

Production-related hazards can include borehole instability, unexplained gas bubbling and gas blowouts (Nimblett et al. 2005). The weakening of gas hydrate-bearing sediment layers has been suggested as a potential trigger for historical and active submarine slope failures globally (e.g. Grozic 2009, Vanneste et al. 2014). With expected increases in sea bottom temperatures as a result of global climate change, the likelihood of submarine slope failures could increase. Submarine landslides threaten offshore infrastructure, lead to land disappearance along coasts and can generate tsunamis (Locat and Lee 2002). Fine-grained hydrate-bearing sediment may pose the greatest risk of all deposit types, as their ability to dissipate excess pore fluid is low, resulting in greater excess pore pressures upon dissociation (Kayen and Lee, 1991). Additionally, natural gas hydrates are most commonly found within fine-grained sediments, increasing their potential risk. A better understanding is needed of the geomechanical behaviour of fine-grained hydrate-bearing sediments before and after dissociation to assess their potential for slope instability and response to production.

Detailed geotechnical testing of in situ hydrate-bearing fine-grained specimens has not yet been possible due to significant hydrate dissociation as a result of pressure and/or temperature changes prior to testing using current coring, transfer and storage techniques. Additionally, emphasis thus far has been on artificially forming hydrate within coarse-grained samples for geotechnical testing in the laboratory, due to the interest in gas production from these deposits. A few experimental investigations have successfully formed hydrate within the pore space of fine-grained soil (Yun et al. 2007, Kim et al. 2013), allowing investigation of its effect on the geomechanical behaviour of the soil. However, the natural distribution habit of hydrate within fine-grained samples is not commonly pore-filling. This limits the applicability of these results to the modelling of natural systems, as pore-scale location of hydrate plays a significant role in the macroscopic physical properties of the sediment (Waite et al. 2009).

This paper presents an experimental technique for the formation of specimens analogous to natural samples that can be used to investigate the strength and stiffness of hydrate-bearing sediment, and the soil behaviour after dissociation.

2 BACKGROUND ON HYDRATE-BEARING FINE-GRAINED SOILS

Methane gas hydrates are most commonly found within fine-grained sediments (Waite et al. 2009). Fine-grained hydrate-bearing sediments have been studied in the Blake Ridge offshore the western U.S., the Gulf of Mexico, offshore Taiwan, Hydrate Ridge offshore western Canada, the Krishna-Godavari Basin offshore India and the Ulleung Basin offshore Korea. Commercial interest is focussed on coarse-grained rather than fine-grained soil, as the higher permeability of sands and gravels facilitates the extraction process (Boswell and Collett 2011).

2.1 Morphology

To understand typical gas hydrate distribution habits within fine-grained soils, the mechanisms driving hydrate formation must be examined. The formation of gas hydrates in natural systems occurs in the presence of a significant gas source, followed by the migration of gas and water to within the hydrate stability zone, where the pressure and temperature conditions within the host sediment are conducive to hydrate precipitation from the gas and water molecules present. Gas migration is a critical component of hydrate formation, as gas generated within the pore space of sediment within the gas hydrate stability zone is generally insufficient to entirely account for the hydrate in a deposit (Kvenvolden 1993).

Several gas migration mechanisms are possible: (1) diffusion, (2) dissolved gas in migrating water, or (3) gas migration in bubble or continuous gas phase. Diffusion would likely not result in significant concentrated hydrate accumulations as it is a relatively slow process (Xu & Ruppel, 1999). The last two models require permeable pathways, with the gas-phase migration model requiring highly permeable interconnected fluid pathways. As a result, hydrate migration and formation is likely to be focussed within more permeable sediment layers, along pre-existing fault systems, or within newly self-created fracture systems (Cook et al. 2008). Fractures can be generated by three physical processes: (1) hydraulic fracturing due to overpressures generated by free gas below the hydrate stability zone (Jain and Juanes 2009) or by high pore fluid pressures (Weinberger and Brown 2006), (2) shear failure along pre-existing soil features driven by pore fluid pressure (Hornbach et al. 2004), and (3) hydrate-induced heave due to the increase in volume from the formation of ice or hydrate crystals, effectively forcing sediment grains apart (Daigle and Dugan 2010).

Preferential fluid flow along fracture planes within fine-grained soils implies the formation and deposition of gas hydrate along fracture walls. The high capillary pressures within the pore space of clay prevents the exsolution of gas, thereby inhibiting the formation of hydrates within clay pores (Torres et al. 2008). As a result, hydrates within fine-grained sediments are most commonly found in a “grain-displacing” morphology, as discrete nodules, planar fracture-filling, layered deposits or complex vein structures (Cook et al. 2008). Hydrates have been found in the pore-filling habit within fine-grained sediments in localized areas of higher permeability and pore size, for example due to local grain size increases associated with layers of silt, silty sand or diatoms (Bahk et al. 2013).

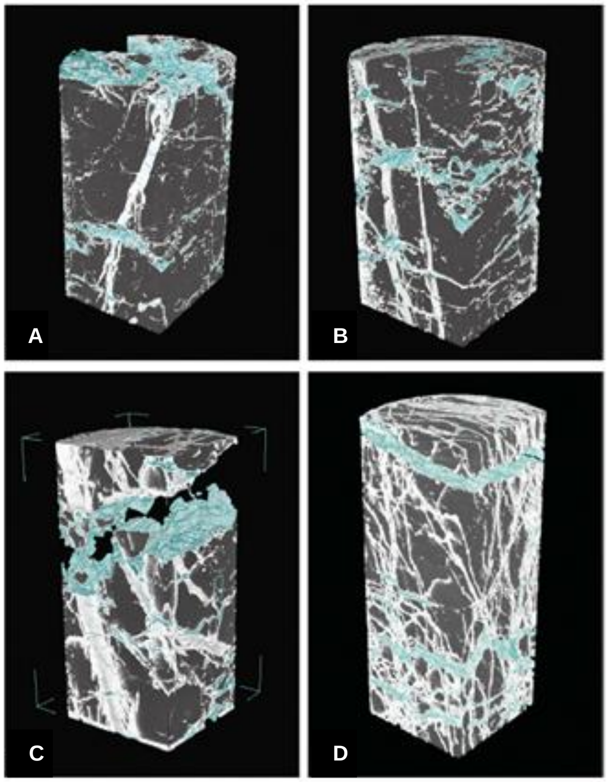

Figure 1. 3-D X-ray CT images of samples from the Krishna-Godavari Basin showing hydrate highlighted as white and ice as blue (modified from Rees et al. 2011).

An example of a typical fracture-hosted fine-grained hydrate-bearing sediment, are samples recovered from the Krishna-Godavari Basin. Host sediments are characterized as high plasticity clays with lower shear strength than would be expected given the in situ vertical effective stress conditions (Priest et al. 2013). Three-dimensional X-ray CT scanning of pressure cores revealed heterogeneous sub-vertical veins dipping at 50-80^{o} from the horizontal in a complex fibrous structure that forks and branches as shown in Figure 1. Rees et al. (2011) suggest that the hydrate distribution is a result of the hydraulic fracturing of the overlying sediment by methane-saturated fluid or methane gas that then flows upwards, infilling the fractures as gas hydrate forms.

2.2 Geomechanical Behaviour of Hydrate-Bearing Fine-Grained Sediments

2.2.1 Previous Studies on Strength and Stiffness Properties

Gas hydrates are stronger and stiffer than the soil in which they form, and their presence has been shown to significantly affect the strength and deformation behaviour of the host sediment.

Yun et al. (2007) carried out undrained triaxial tests on laboratory-formed, hydrate-bearing kaolinite clay and agglomerated precipitated silt with THF (tetrahydrofuran) hydrate saturations of 0%, 50% and 100% within the pore space. A THF-water solution was mixed with dry soils to form a saturated paste, the specimen was consolidated to the target effective stress and then cooled to below zero. An increase in shear strength (q_{max}) and stiffness was observed with increasing hydrate concentration, however the higher the effective confining stress, the lower the impact of hydrates on the normalized strength. It was determined by the authors that at low hydrate saturations (<40%), the soil stiffness and frictional strength dominate the mechanical properties, while hydrate will dominate the mechanical behaviour at high saturations.

While hydrate is unlikely to form at high concentrations within the pore space of fine-grained soils, a hydrate-dominated response has also been observed in natural hydrate-bearing soil. Undrained shear strength testing with no effective stress imposed was carried out on pressure cores of fine-grained natural sediments from the Gulf of Mexico using a cone penetrometer, demonstrating a higher undrained strength in hydrate-bearing sediments than non-hydrate bearing sediments (Yun et al. 2006). In situ cone resistance using piezocones during offshore drilling in Nigeria showed increased strength in shallow hydrate-bearing sediments (Sultan et al. 2007).

2.2.2 Hypothesized Impact of Hydrate Veins on Geomechanical Behaviour

To date, the understanding of the effect of gas hydrate on its host sediment is within the context of pore-filling hydrates within coarse-grained and fine-grained soils. That is, if the hydrate is located within the pore space, its effects on the strength at low hydrate saturations will be much less than if the pore space is entirely filled with hydrate, effectively cementing the soil matrix. However, the correlations developed relating homogeneously-distributed hydrate saturation in the pore space to strength and stiffness of the soil may not apply to complex, branching, fracture-hosted hydrate deposits in fine-grained sediment.

The potential effects of hydrate veins on the strength of a fine-grained soil is examined within the framework of the Mohr-Coulomb failure criterion as given by Equation 1, which defines the shear strength in terms of the effective friction angle ϕ', the effective cohesion c', and the effective normal stress σ', which is itself a function of total stress σ and pore pressure u:

$$\tau = \sigma' \tan \phi' + c' = (\sigma - u) \tan \phi' + c' \qquad [1]$$

A thick, vertically-oriented hydrate vein extending continuously through a sample similar to the ones pictured in Figure 1C, could end up bearing a large portion of applied load if it does not yield, increasing the strength of the material as a result of this load sharing. This would manifest in the soil response as an increase in cohesion.

If less load is transferred to the surrounding soil due to the much stronger hydrate vein, then the pore pressure response to the deviatoric loading may not be as high than it otherwise would be. This phenomena is best explained using the equation for excess pore water presure given in Equation 2 in terms of Skempton's pore pressure parameters A and B (Skempton, 1954):

$$u = B\,(\Delta\sigma_3 + A\,(\Delta\sigma_1 - \Delta\sigma_3)) \qquad [2]$$

Considering a fully saturated soil (B=1) containing hydrate veins, the A parameter which determines the pore pressure response to deviatoric load would be lower if the veins are aligned parallel to the principal stress direction. The result of this would be an a higher measured shear strength of the soil due to less pore pressure build up.

As a result of these two potential mechanisms, an increase in strength at relatively low hydrate saturations should be expected, given that the veins are aligned with the principal stress axis (vertical). This will result in a greater increase in strength than would be expected using the previously developed relationships, for sand bearing-hydrates, between the strength and the hydrate saturation within the pore space of the host sediment.

Similarly, the stiffness of a vertically-oriented hydrate vein is much greater than the surrounding soil, and if its yield strength is not reached, then the overall deformation experienced by the specimen will be reduced.

As hydrate veins/layers/nodules are not always vertical, these hypotheses may not necessarily apply in all natural cases. However hydrate veins, oriented towards the principal stress direction could reasonably be expected to represent the maximum impact that the hydrate will have on the strength, stiffness and deformation behaviour of a specimen, and therefore laboratory techniques will focus on forming hydrates in this distribution habit.

3 TECHNIQUES FOR THE PREPARATION OF LABORATORY-FORMED HYDRATE-BEARING FINE-GRAINED SOILS

Due to the difficulty in preserving and testing natural, hydrate-bearing, fine-grained soils to evaluate the impact that hydrate veins will have on the geomechanical behaviour, a laboratory analogue to the complex, fibrous natural vein structures has been developed. A simplified vertical, cylindrical, synthetic hydrate vein was created at the centre of a triaxial soil specimen, with the hydrate vein completely encircled by soil. This distribution habit was selected in order to simplify the formation method, while also creating an axisymmetric specimen that will respond to horizontal stresses (σ_3) axisymmetrically in the radial direction ($\varepsilon_2 = \varepsilon_3 = \varepsilon_r$), thereby simplifying future geomechanical analysis of the specimen.

3.1 Materials

3.1.1 Fine-Grained Soil

Due to the unavailability of natural, formerly gas hydrate-bearing soil, a laboratory-mixed replicate of a typical fine-grained soil in which marine gas hydrates are hosted, was constructed. Using controlled specimens ensures the soil is conducive to repeatable laboratory investigations.

Soil characterization has been carried out on natural fine-grained soil (after hydrate dissociation) in several regions and average properties are shown in Table 1. The fracture-hosted gas hydrate-bearing soil of the Krishna-Godavari Basin in the Indian Ocean, shown in Figure 1, is has a grain size ranging from silty clay to clayey silt, with Atterberg limits indicating highly plastic clay or compressible silt. In the Ulleung Basin, fracture-filling hydrates are present within silt to clayey silt of medium to high plasticity. While more massive, layered gas hydrate-hosted Northern Gulf of Mexico sediment contains a significantly higher clay fraction.

Table 1. Soil characteristics of different natural hydrate-bearing soils and laboratory mixed clay

Characteristics (%)	Krishna-Godavari Basin[1]	Ulleung Basin[2]	Gulf of Mexico[1]	Experim-ental Soil
Average Sand	5	0	1	1.4
Average Silt	55	80	22	63.6
Average Clay	40	20	77	35
Liquid limit range	70-98	12-129	N/A	33
Plastic limit range	33-49	17-88	N/A	18

[1] Winters (2011)

[2] Lee et al. (2011)

To form the experimental specimens of fine-grained soil, a mixture is formed, by weight, of 35% EPK Kaolin and 65% Sil Industrial Minerals Flour 325 mesh ground silica. The grain size distribution is determined through particle size analysis, while liquid and plastic limits are determined using the fall cone penetrometer, and ASTM D4318, respectively. The experimental soil is a good approximation of natural hydrate-bearing fine-grained soil in terms of grain size, as illustrated in Figure 2, comparing the grain size of the experimental soil with formerly hydrate-bearing fine-grained soil recovered from the Krishna-Godavari Basin. However, the experimental soil is of much lower plasticity than the natural marine clays due to the high silt content and the use of kaolinite rather than a more plastic clay mineral. The liquid limit is 33%, and the plastic limit is 18%.

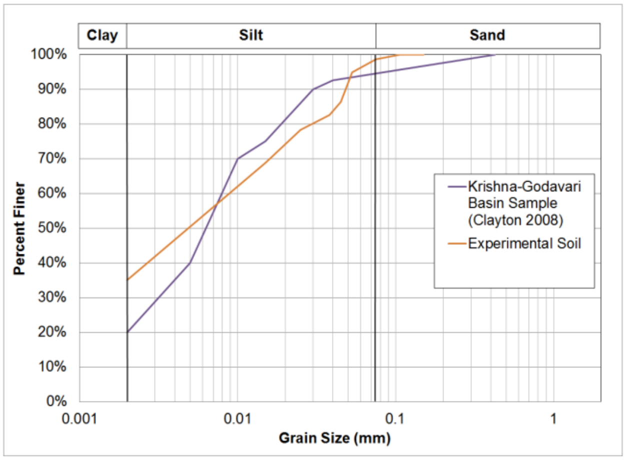

Figure 2. Grain size distribution curve of the artificially formed soil compared to formerly gas-hydrate-bearing fine-grained soil from the Krishna Godavari (from Clayton et al. 2008).

3.1.2 Tetrahydrofuran Hydrate

Tetrohydrofuran (THF) (C_4H_8O) hydrate was used in this study, as it is a compound that is completely miscible in water, allowing for rapid and homogeneous hydrate synthesis at atmospheric pressure and low temperature. This synthetic hydrate was used as a proxy for methane hydrate, as methane hydrate requires much longer, and much higher pressures to form, making testing procedures significantly more complex.

THF is liquid at atmospheric conditions, thus THF hydrate does not produce gas upon dissociation. Therefore, THF is not suitable to study the post-dissociation effects of the hydrate on the strength and deformation behaviour of the soil. Additionally, THF forms a Structure II hydrate, meaning that the THF molecules fill only the large cavities, while methane fills large and small cavities as a Structure I hydrate. However, despite their chemical differences, they are very similar mechanically in stiffness and strength (Sloan and Koh 2007). Therefore, THF hydrate was selected as an analogue to methane hydrate for the purpose of basic geomechanical studies.

THF and water form hydrate when mixed at a molar ratio of 1:17, which melts at 4.15°C. Due to the much higher vapour pressure of THF as compared to water, preferential evaporation of THF can lead to incomplete hydrate formation. Carrying out preliminary differential scanning calorimetry measurements, Zeng et al. (2006) determined that a combination of ice and THF hydrate was obtained by using a molar ratio of 1:17, and that using a ratio of 1:15 would ensure complete THF hydrate formation when cooled to below 2.35°C. The reformation of THF hydrate is accelerated after dissociating the hydrate, suggesting a “memory effect” (Zeng et al. 2006). In this research, THF hydrate was prepared using an excess THF molar ratio of 1:15 by cooling the mixture in a closed vial to below 2°C.

3.2 Specimen Preparation

The soil mixture was prepared using 35% kaolin and 65% silica flour by weight, at a water content of 55% (just over 1.5 times the liquid limit of 33%) to form a slurry. The slurry was pre-consolidated one-dimensionally in a 20.6 cm diameter consolidation cell under a maximum vertical effective stress of 100 kPa. The soil was drained vertically through the top and bottom of the chamber over a week, and then subsequently unloaded in fully drained conditions to prevent suction from developing. Samples were then taken by slowly pushing four 70 mm diameter cylindrical sampling tubes into the consolidated soil. Each specimen was slowly extruded vertically from the sampling tubes, ensuring minimal disturbance. The final specimen was carefully weighed and measured, with dimensions of approximately 70 mm diameter by 140 mm height. Filter strips were placed radially around the extruded specimen, and filter papers applied to the top and bottom, to maximize drainage. The prepared specimen was then then placed in a latex membrane and a split mold assembled around the specimen to maintain structural integrity during subsequent formation steps. Pre-cooling involved placing the specimen in a refrigerator, where it was cooled overnight to below 2^{o}C, but kept above 0^{o}C to avoid freezing.

3.2.1 Vein Formation

A hydrate vein was formed within the specimen using the procedure outlined below. As shown in Figure 3a, the mold containing the cooled soil was placed under a drill press, where augers of 6.35, 9.525 and 12.7 mm diameter can be used to drill completely through the specimen into a base plate to form a continuous cylindrical hole. The spoiled soil removed from the newly formed vein was kept in a moisture bag, and the specimen subsequently re-cooled back into the THF hydrate stability field. Previously prepared THF hydrate at a molar ratio of 1:15 was dissociated under a fume hood in a closed vial, so that hydrate reformation was faster due to the ‘memory’ effect. The specimen containing the bored hole was then placed under a fume hood and a portion of the spoils were tamped down onto the base plate to form a thin layer of soil separating the base plate from the soon to be introduced THF-water mixture. This was carried out to ensure that the THF-water mixture did not leak out while THF hydrate was forming in the vein. The THF-water mixture was then poured into the vein as shown in Figure 3b. The specimen and THF-water liquid was covered using the triaxial top cap and then cooled to -10^{o}C to accelerate the process of hydrate formation. After 75 min at -10^{o}C, a thin layer of spoiled soil was tamped over the top of the now-fully-formed, stiff THF hydrate. Subsequent to the placement of the thin soil layer on top of the vein, the specimen was cooled to below 2.15^{o}C, but again kept above 0^{o}C to prevent further soil freezing.

Figure 3: Hydrate vein formation within soil

The soil layers at the top and bottom of the hydrate vein serve the purpose of isolating the hydrate vein from free water in the base and top cap. This is done because in addition to dissociation, hydrate breakdown can occur due to dissolution, whereby insufficient hydrate-former molecules (in this case THF) in the surrounding water leads to a concentration-driven breakdown of the hydrate in contact with free water. It was determined in preliminary testing that contact between the THF hydrate and the pure pore water in the soil forming the vein walls did not lead to significant THF hydrate dissolution over the time periods required by the testing procedure. However, hydrate-vein-bearing specimens kept within the stability field were found to have dissociated after approximately 6 days, perhaps due to this phenomena.

The above procedure has been designed such that the hydrate is formed as quickly as possible within the pre-drilled structure. In a preliminary testing phase, it was found that a liquid mixture in contact with an open vein structure can compromise the structural integrity of the vein if left for extended periods of time, with sloughing observed from the sides of the vein into the liquid, and then precipitating onto the bottom of the open vein structure, as well as slow deformation and creep of the soil inward into the open vein structure. Additionally, significant freezing and subsequent thawing of the soil is prevented by the short vein formation period.

4 EXPERIMENTAL PROCEDURE

This section outlines the steps taken to allow for future geomechanical investigations on hydrate-vein-bearing specimens. The driving philosophy is to keep the hydrate-bearing specimen within the stability field at all times, as dissociation will lead to vein closure at high pressures, and result in the infiltration of THF-water mixture from the vein into the surrounding soil.

4.1 Testing Apparatus

To investigate the behaviour of hydrate veins in fine-grained soil, a double walled triaxial system is to be used in future studies, allowing for cell pressures of up to 2 MPa, with de-aired water as the cell fluid. The system was modified so as to maintain the specimen within the hydrate stability zone by keeping it below 2°C. To accomplish this, a refrigerated circulator was used to pump coolant fluid into a network of copper pipes submerged within the cell water, effectively maintaining the cell fluid below 2°C. The cell was insulated using foam insulation to prevent warming of the cell fluid.

4.2 Specimen Mounting and Cell Assembly

The transfer of the specimen from the cooling chamber to the triaxial cell was done as quickly as possible, so that the time that the hydrate vein was exposed to room temperature was minimized. A wet mounting technique was employed, whereby the specimen drainage line was filled with de-aired distilled water and porous disks and filter paper were saturated. The split mold containing the specimen was removed from its cooling chamber, and was mounted on a pre-cooled base. O-rings were applied around the membrane at the top and bottom cap, in order to ensure a proper seal. A radial strain gauge was attached at the specimen mid-height. The triaxial chamber was then partially assembled, as shown in Figure 4a. The cell walls were installed, and the inner cell was filled with crushed ice to the top of the specimen as shown in Figure 4b. The cell assembly was then completed, and de-aired, distilled, cooled (T<4°C) water used to fill the cell. The axial load piston was brought into contact with the top cap. By this method, the specimen was only outside of the hydrate stability zone for 10 minutes, from removal from the cooling chamber to the filling of the chamber with crushed ice.

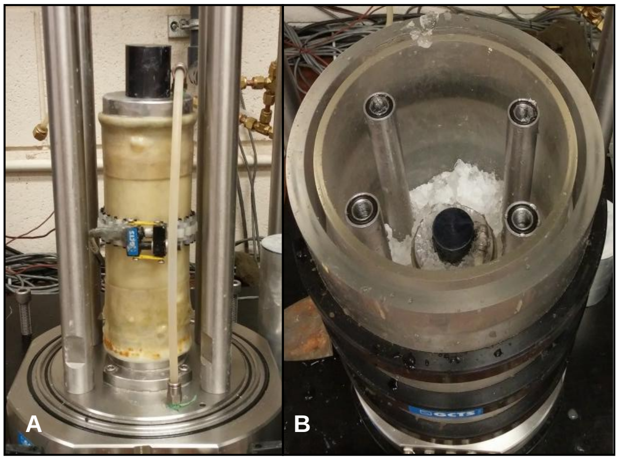

Figure 4: Mounting technique and triaxial cell assembly.

4.3 Application of Stress

After allowing the temperature within the cell to stabilize, stress was applied to the specimen. Specimens were reconsolidated to 100 kPa effective confining pressure at a cell pressure of 500 kPa and back pressure of 400 kPa to ensure that any air present within the specimen is driven into solution. The specimen was drained through the top cap, while the pore pressure response to consolidation was measured using a gauge in the base cap. The position of the back pressure piston can be used to calculate the volume of water drained from the specimen and hence the change in void ratio. The axial load bar is carefully brought into contact with the specimen cap to allow for axial deformation readings, while radial deformation is monitored using the radial strain gauge. If the hydrate-vein-bearing specimen in the triaxial cell can be reconsolidated to its pre-consolidation pressure, while preserving the hydrate vein structure, further geotechnical testing can be carried out to test the hypotheses put forward in Section 2.2.2.

5 PRELIMINARY RESULTS AND DISCUSSION

An extensive testing program was carried out in order to refine the previously outlined steps in the Section 3 and Section 4. The goal of this testing program was to determine whether or not it was possible to consistently form hydrate veins within a fine-grained soil matrix, and to keep this hydrate vein intact when transferring the specimen to the triaxial system and applying effective stresses. During this program, only veins of 12.7 mm diameter were installed in the soil.

To demonstrate the efficacy of the steps in Section 3 and 4, Figure 5 shows hydrate veins present at two of the steps in this process, with the hydrate veins outlined in red. Figure 5a shows an intact hydrate vein after forming the specimen using the steps outlined in Section 3, and maintaining the specimen for 24 hours within the hydrate stability field using the cooling chamber set to a temperature of 2°C. Figure 5b shows a hydrate vein after mounting the specimen in the triaxial system, applying 500 kPa of cell pressure (but no drainage allowed), and keeping it within the triaxial system for 24 hours. It can be seen in Figure 5b that the hydrate vein is separated into three distinct “chunks”. This is most likely due to dissociation, as the removal of stresses and dismounting of the specimen from the triaxial cell takes approximately 15 minutes, and partial dissociation may occur within this period of time. However, this may also be due to the fact that the specimen underwent some bending when pressurized to 500kPa at zero effective stress.

Although not pictured, the hydrate veins remain intact when reconsolidated to the pre-consolidation pressure within the triaxial system.

Figure 5: Laboratory-formed hydrate veins (outlined in red) within soil after (A) being kept within the stability field (<2.15^{o}C) for 24 hours and (B) kept at a cell pressure of 500 kPa with no effective stress for 24 hours.

6 CONCLUSIONS

Marine hydrates are a potential geohazard, and fine-grained soils, which host the majority of the world's hydrates, pose a significant risk. Hydrates form within fracture-hosted, fine-grained deposits in fibrous, sub-vertical, interconnected, vein structures. The geomechanical behaviour of hydrate-vein-bearing fine-grained soils is poorly understood at present, due to the difficulty in testing in situ samples and forming analogous laboratory specimens. It is hypothesized that hydrate veins will result in a general increase in both the strength and stiffness of the material. Preliminary results indicate that a simplified, cylindrical tetrahydrofuran hydrate vein can be formed and preserved within a laboratory-mixed fine-grained soil by following the procedure outlined within this paper. Results indicate that specimens can be isotropically reconsolidated to a pre-consolidation stress of 100 kPa within a cooled triaxial cell while preserving the hydrate vein structure within the silt-clay mixture. Further work is required to determine the geomechanical effect that the hydrate vein structures will have on the strength, stiffness and consolidation behaviour of the fine-grained soil. With human activity on the sea floor intensifying, and sea bottom temperatures increasing as a result of climate change, studying the geomechanical behaviour of fine-grained sediments hosting hydrates will allow for an improvement in the understanding and prediction of this geohazard.

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REFERENCES

Bahk, J.-J., Kim, D.-H., Chun, J.-H., Son, B.-K., Kim, J.-H., Ryu, B.-J., Torres, M.E., Riedel, M. and Schulteiss, P. 2013. Gas hydrate occurrences and their relation to host sediment properties: results from second Ulleung Basin Gas hydrate drilling expedition, east sea, *Marine and Petroleum Geology*, 47: 21-2.

Boswell, R. and Collett, T.S. 2011. Current perspectives on gas hydrate resources, *Energy & environmental science*, 4(*4*):1206-1215.

Clayton, C., Kingston, E., Priest, J., Schultheiss, P. and NGHP Expedition 01 Scientific Party. 2008. Testing of pressurised cores containing gas hydrate from deep ocean sediments, *Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008)*, Vancouver, British Columbia, Canada.

Cook, A.E., Goldberg, D., and Kleinberg, R.L. 2008. Fracture-controlled systems in the northern Gulf of Mexico, *Marine and Petroleum Geology*, 25(*9*): 932-941.

Daigle, H., and Dugan, B. 2010. Origin and evolution of fracture-hosted methane hydrate deposits, *Journal of Geophysical Research: Solid Earth (1978–2012)*, 115(*B11*).

Grozic, J.L.H. 2010. Interplay between gas hydrates and submarine slope failures, in *Submarine Mass Movements and their Consequences*, Springer Netherlands, 11-30.

Hornbach, M.J., Saffer, D.M., and Holbrook, W.S. 2004. Critically pressured free-gas reservoirs below gas-hydrate provinces. *Nature*, 427(*6970*): 142-144.

Jain, A.K., and Juanes R. 2009. Preferential Mode of gas invasion in sediments: Grain-scale mechanistic model of coupled multiphase fluid flow and sediment mechanics, *Journal of Geophysical Research: Solid Earth (1978–2012)*, 114(*B8*).

Kayen, R.E. and Lee H.J. 1991. Pleistocene slope instability of gas hydrate-laden sediment on the Beaufort sea margin, *Marine Georesources & Geotechnology*, 10:125-141.

Kim, H.-S., Cho, G.-C., and Kwon, T.-H. 2013. Effect of CO_2 hydrate formation on seismic wave velocities of fine-grained sediments, *Geochemistry Geophysics Geosystems*, 14: 1787-1799.

Kvenvolden, K.A. 1993. Gas hydrates-geological perspective and climate change, *Reviews of Geophysics*, 31(*2*): 173-187.

Lee, C., Yun, T.S., Lee, J.S., Bahk, J.J. and Santamarina, J.C. 2011. Geotechnical characterization of marine sediments in the Ulleung Basin, East Sea. *Engineering Geology*, 117(*1*): 151-158.

Masui, A., Haneda, H., Ogata, Y., and Aoki, K. 2006. Triaxial Compression test on submarine sediment containing methane hydrate in deep sea off the coast off Japan, *Proceedings of the 41st Annual Conference, Japanese Geotechnical Society*.

Nimblett, J.N., Shipp, R.C., and Strijbos, F. 2005. Gas hydrate as a drilling hazard: examples from global deepwater settings, *Offshore Technology Conference*, Houston, Texas, USA, 17476: 1-7.

Locat, J. and Lee, H.J. 2002. Submarine landslides: advances and challenges, *Canadian Geotechnical Journal*, 39(*1*): 193-212.

Rees, E.V., Priest, J.A. and Clayton, C.R.I. 2011. The structure of methane gas hydrate bearing sediments from the Krishna–Godavari Basin as seen from Micro-CT scanning, *Marine and Petroleum Geology*, 28(*7*): 1283-1293.

Priest, J.A., Clayton, C.R.I. and Rees, E.V.L. 2014. Potential impact of gas hydrate and its dissociation on the strength of host sediment in the Krishna–Godavari Basin, *Marine and Petroleum Geology*, 58: 187-198.

Skempton, A.W. 1954. The pore-pressure coefficients A and B, *Geotechnique*, 4(*4*): 143-147.

Sloan, E.D., Jr., and Koh, C. 2007. Clathrate hydrates of natural gases. CRC press.

Soga, K., Lee, S.L., Ng, M.Y.A., & Klar, A. 2006. Characterisation and engineering properties of methane hydrate soils, *Characterisation and engineering properties of natural soils*, 2591-2642.

Sultan, N., Voisset, M., Marsset, T., Vernant, A.M., Cauquil, E., Colliat, J.L. and Curinier, V. 2007. Detection of free gas and gas hydrate based on 3D seismic data and cone penetration testing: An example from the Nigerian Continental Slope, *Marine Geology*, 240(*1*): 235-255.

Torres, M.E., Tréhu, A.M., Cespedes, N., Kastner, M., Wortmann, U.G., Kim, J.-H., Long, P., Malinvernof, A., Pohlman, J.W., Riedel, M. and Collett, T. 2008. Methane hydrate formation in turbidite sediments of northern Cascadia, IODP Expedition 311, *Earth and Planetary Science Letters*, 271(*1*): 170-180.

Vanneste, M., Sultan, N., Garziglia, S., Forsberg, C., and L'Heureux, J.-S. 2014. Seafloor instabilities and sediment deformation processes: the need for integrated, multi-disciplinary investigations, *Marine Geology*, 352: 183-214.

Waite, W.F., Santamarina, J.C., Cortes, D.D., Dugan, B., Espinoza, D.N., Germaine, J., Jang, J., Jung, J.W., Kneafsey, T.J., Shin, H., Soga, K., Winters, W.J., Yun, T.-S. 2009. Physical properties of hydrate-bearing sediments, *Reviews of Geophysics*, 47(*4*).

Winters, W.J. 2011. Physical and geotechnical properties of gas-hydrate-bearing sediment from offshore India and the Northern Cascadia margin compared to other hydrate reservoirs, *Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011)*, Edinburgh, Scotland, United Kingdom.

Weinberger, J.L. and Brown, K.M. 2006. Fracture networks and hydrate distribution at Hydrate Ridge, Oregon, *Earth and Planetary Science Letters*, 245(*1*): 123-136.

Xu, W. and Ruppel, C. 1999. Predicting the occurrence, distribution, and evolution of methane gas hydrate in porous marine sediments, *Journal of Geophysical Research: Solid Earth (1978-2012)*, 104(*B3*): 5081-5095.

Yun, T.S., Narsilio, G.A. and Santamarina, J.C. 2006. Physical characterization of core samples recovered from Gulf of Mexico, *Marine and Petroleum Geology*, 23(*9*): 893-900.

Yun, T.S., Santamarina, J.C., Ruppel, C. 2007. Mechanical properties of sand, silt, and clay containing tetrahydrofuran hydrate, *Journal of Geophysical Research: Solid Earth (1978-2012)*, 112(*B4*).

Zeng, H., Wilson, L.D., Walker, V.K., & Ripmeester, J.A. 2006. Effect of antifreeze proteins on the nucleation, growth, and the memory effect during tetrahydrofuran clathrate hydrate formation, *Journal of the American Chemical Society*, 128(*9*): 2844-2850.