GEOMECHANICAL PROPERTIES OF SYNTHETIC HYDRATE BEARING SEDIMENTS

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ABSTRACT

Geomechanical properties of methane hydrate bearing sediments are important for natural gas production from hydrate-bearing reservoirs, well stability, slope stability, and location and design of subsea equipment platforms. However, changes occurring within methane hydrate bearing sediments subjected to stress are not currently well understood, and only a limited number of experiments have been conducted in the laboratory. Due to the dynamic nature of methane hydrate within sediment pore space, hydrate-cemented sediment subjected to compression and shear are known to exhibit unique behavior such as cement (hydrate) redistribution, self preservation, and memory effect, which can impact overall strength and geophysical properties of the sediment. It is important therefore to study the behavior of hydrate bearing sediment under the realistic temperature, pressure, and chemical conditions of a hydrate reservoir. Recently, an X-ray transparent triaxial test cell was developed which can apply pressures up to 25 MPa confining stress and 100 MPa axial stress under controlled temperatures (-10°C up to +50°C). Using this cell, methane hydrate can be synthesized inside a sediment pack before applying compression. In addition, the cell is capable of measuring seismic properties of the sample before, during, and after the compression test. This paper will show some examples of experiments on synthetic, methane-hydrate bearing sediment samples, tested under axial compression.

Keywords: Triaxial compression, X-Ray CT, seismic properties.

INTRODUCTION

Geomechanical properties of gas-hydrate bearing sediments provide information on how sub-seafloor or permafrost sediments would respond to the stresses applied through lithostatic loading, wellbores, and/or subsea equipment platforms. In addition, because gas hydrate is sensitive to changes in pressure and temperature, the strength and stability of such sediments can change depending on environmental conditions. Such
would be the case when exploiting gas hydrate reservoirs, or when wells carrying warm geofluids penetrate gas hydrate zones during oil exploration [1, 2]. Global environmental changes may too alter hydrate stability in the sub-seafloor, and so geomechanical properties are also needed when evaluating submarine slope stability in hydrate bearing regions [3, 4]. As our understanding of the role of gas hydrate in sea floor stability improves and as research moves further towards the exploitation of hydrate resources, the need for accurate knowledge of the geomechanical properties of hydrate bearing sediments increases.

Unlike geophysical properties that can be measured in the field, strength and time dependant behavior (basic geomechanical properties) are best measured under laboratory conditions. This creates problems when dealing with natural gas hydrates due to the high pressure and low temperature conditions of hydrate stability. Early measurements of hydrate bearing sediment geomechanical properties were made using tetrahydrofuran or THF hydrate [5, 6]. THF is a low pressure hydrate former, which allows for laboratory experiments to be conducted without the use of a high pressure apparatus. However, as THF forms hydrate without a gas phase and has a different structure than methane hydrate [7], there is still debate as to the applicability of the results from THF hydrate experiments to natural hydrate deposits [8, 9]. More recently, equipment has been designed so that the mechanical properties of methane hydrate bearing sediments can be evaluated [10-13], but the results from such experiments are still in preliminary stages.

The main problems faced by those wishing to form methane hydrate in the laboratory are in creating hydrate that is analogous to that found in the field, and with homogeneous hydrate distribution so that results can be interpreted and extended with confidence. These problems have been addressed by several researchers [9, 14], however, without a method of quantifying hydrate distribution in a sediment, it remains unclear as to whether current methods are acceptable. X-Ray computed tomography (CT) scanning of hydrate bearing sediments has been shown to be a satisfactory method to determine hydrate distribution in sediment samples [15-18], but this capability is not available in all laboratories.

As noted previously, the increasing potential for exploitation of the world’s hydrate resources requires understanding of how sediments behave during hydrate dissociation, and geomechanical failure must be well understood. The collection of geophysical data in conjunction with mechanical data would provide information on potential seismic precursors to sediment failure or dissociation that would be valuable to those wishing to exploit a hydrate resource. As a result, the ability to measure geomechanical data in conjunction with geophysical (seismic) signatures is highly desirable.

We report on our first experiments on the mechanical properties of methane gas hydrate bearing sediments, and detail the capabilities of a specially designed cell to measure geomechanical and geophysical properties of these materials with concurrent X-Ray CT scanning to aid in interpretation of sediment structure.

**APPARATUS AND SPECIMEN PREPARATION**

**Gas Hydrate Geomechanical Cell**

The apparatus developed for the work described in this paper was designed for simultaneous triaxial compression tests and seismic velocity measurements. In addition, samples can also be imaged by CT scanning during testing. The resulting tool is referred to as the Gas Hydrate Geomechanical Cell (GHGC), shown in Figure 1.

The GHGC uses hydraulic pressure to apply stress to the column of sediment placed within. Two pressure chambers, C1 and C3 in Figure 1, apply the confining and axial stresses respectively. Radial confining pressure is controlled using a high-pressure syringe pump, with the confining fluid injected through the top of the cell (the cell can be used in the horizontal orientation as well). Axial load is applied via C3, also controlled by another high pressure syringe pump. Pressure is applied to the sample by a piston at the base of the sample. Due to the geometry of the piston, the axial pressure applied to the sample within the apparatus is four times greater than the applied pressure. Temperature is controlled by a water jacket placed over the aluminum confining cylinder.
The pressure capabilities of the GHGC (up to 25MPa for confining pressure, and 100MPa for axial load), and the facility to apply temperatures between -10°C and +50°C allow the formation of methane hydrate within a sediment. The aluminum confining cylinder allows for X-Ray transparency within the portion on the cell where the sample resides. In addition, compression and torsion wave transducers were built into the end caps, so that seismic waves could be propagated through the sample during axial compression.

**Figure 1. Schematic of the GHGC**

**Sample Preparation**

The chief material used to create each sample was F-110 Ottawa sand (100% silica sand, rounded to sub-angular grains, 120µm average grain size [19]). In addition, silica flour (SIL-CO-SIL®45: 100% ground silica, 40µm average grain size) and kaolinite (10 µm average grain size) were also used in a number of tests to vary sediment type. The content of each sample is given in Table 1.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Dry Materials</th>
<th>Porosity</th>
<th>Water Sat</th>
<th>Hydrate Sat</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-M1</td>
<td>100% F-110</td>
<td>33.5%</td>
<td>21.1%</td>
<td>-</td>
</tr>
<tr>
<td>FS-M1</td>
<td>100% F-110</td>
<td>33.4%</td>
<td>21.1%</td>
<td>-</td>
</tr>
<tr>
<td>SK-M1</td>
<td>90% F-110 10% kaolinite</td>
<td>28.8%</td>
<td>24.9%</td>
<td>-</td>
</tr>
<tr>
<td>SSi-M1</td>
<td>90% F-110 10% S. Flour</td>
<td>30.9%</td>
<td>23.7%</td>
<td>-</td>
</tr>
<tr>
<td>HS-M1</td>
<td>100% F-110</td>
<td>33.0%</td>
<td>21.2%</td>
<td>13.6%</td>
</tr>
<tr>
<td>HS-M2</td>
<td>100% F-110</td>
<td>30.1%</td>
<td>24.5%</td>
<td>16.8%</td>
</tr>
</tbody>
</table>

S = sand, K = kaolinite, Si = Silica Flour, F = frozen, H = hydrate, M = multi-stage test.

**Table 1. Properties of samples tested in the GHGC**

Samples were prepared by adding a predetermined quantity of distilled, de-ionized water to the dry material. Actual sample properties are given in Table 1. The water and dry materials were mixed together inside a plastic container before being packed into a rubber membrane attached to the base piston of the GHGC by tamping in layers. The sample geometry was then measured before the GHGC was fully assembled around the sediment sample.

**EXPERIMENTAL METHODS**

**Triaxial Testing**

The shear strength of a sediment is typically described in terms of either the angle of shearing resistance, termed the friction angle $\Phi$, or by peak or critical strength. These parameters can be determined by carrying out triaxial compression testing. Conventional triaxial testing compresses a column of sediment at a constant strain rate until the sample fails. By measuring the changes in stress that must be applied axially to the sediment to maintain a constant strain rate, Mohr’s circle can be plotted (Figure 2). The tangent of the resultant circle passing through the origin will have the equation $\tau = \sigma \tan \Phi$ where $\tau$ is shear stress and $\sigma$ is effective normal stress [20]. As the shear strength of a sediment will change with effective stress, the friction angle must be determined by plotting Mohr’s circle for several effective stresses to obtain the failure envelope.
This is customarily done in the laboratory by conducting 3 triaxial compression tests on similar samples at different effective stresses [20].

**Figure 2.** Mohr’s circle with the Coulomb failure criterion. Circle is plotted by finding the principle effective stresses $\sigma_1'$ and $\sigma_3'$ at failure. The tangent of the circle passing through the origin describes the Coulomb failure criterion in terms of the peak shear stress $\tau_{\text{peak}}$ and friction angle $\Phi$.

In a standard triaxial system, where assembly is relatively fast and the samples being tested are permeable, conventional triaxial testing is not necessarily a lengthy process. The samples tested in the GHGC contain methane hydrate, and each sample takes several days to form prior to testing. In addition, the formation morphology of methane hydrate in sediments can often be heterogeneous and unpredictable when formed under partially saturated conditions, as seen from numerous X-ray CT scans conducted by the authors. Considering the length of time to form methane hydrate and the potential variability in samples into account, it was decided that multi-stage triaxial testing would be employed to obtain strength data from these samples.

Multi-stage triaxial testing allows for a failure envelope to be obtained for a sediment by cyclically loading a single sample to numerous failure points [21]. Multi-stage testing maximizes the data that can be gathered for a particular sediment type and hydrate content so that failure envelopes can be obtained with confidence. The drawback of the multi-stage test is that the sample cannot be taken to actual failure at each loading step, as this would distort the results for the subsequent loading cycles. “Failure” in a multistage triaxial test is therefore defined as the point where the rate of stress increase in the sample becomes zero for each strain increment. The sample is subsequently not pushed past the peak strength point as total strain ideally needs to be kept under 10% for the duration of the test. This can lead to uncertainty when comparing multi-stage testing to conventional triaxial testing.

**Figure 3.** A comparison of the Mohr circles generated by the conventional triaxial tests on F-110 sand (solid line), and the multi-stage triaxial test (dashed line).

In order to evaluate the multistage testing method, a conventional triaxial test was conducted on 20% water saturated F-110 sand, which was subsequently compared to a multi-stage triaxial test on a similar sample. Figure 3 shows the Mohr circles of stress and the failure envelopes from both tests. It can be seen that the multi-stage test of one F-110 sample compares favorably with the conventional testing of three separate F-110 samples, although the peak strengths gained from the multistage test are slightly higher than the conventional testing.

**Seismic Measurements**

The base piston of the GHGC contains compression and torsional shear seismic sources. The top end plug in contact with the sample contains matched pairs of accelerometers oriented in the axial and tangential direction (see Figure 1.). The output from the latter pair is combined to cancel unwanted flexural motions while enhancing the circular (torsion) motions. Each piezoceramic source is driven by a Ricker wavelet with a ~100V peak amplitude and with a central frequency well below the resonance frequency of the source. During triaxial compression tests, compression and torsional waves transmitted through a sample
are monitored and recorded for their travel times. Prior to the experiments, the system delay time, which is necessary for determining the velocities of a sample from the measured propagation time of the waves, was measured using a calibration sample with known seismic velocities.

**Test Procedure**

Once the cell was fully assembled, the multistage triaxial tests were conducted under drained conditions. During the experiment, an axial load was applied to the sample at a strain rate of 0.1%/min. The resulting axial displacement was measured using a LVDT (linear variable displacement transducer) attached to the inlet tube directly connected to the bottom piston. The pressure in the axial piston chamber (converted to the axial stress on the sample by multiplying a factor of 4) was recorded every 2 minutes along with the axial displacement which was converted to strain. Approximate volume changes in the sample were monitored by the fluid volume expelled from the confining pressure chamber (C1 in Figure 1) while a syringe pump maintained the original starting confining pressure.

**Figure 4.** Multistage test results for sample FS-M1 (20% Ice in F-110 sand).

In Stage 1, the samples were isotropically consolidated first to 0.28 MPa. Subsequently, a loading test was conducted until the “failure” of the sample was observed. In all tests, the “failure” point was assumed to have been reached once the rate of stress increase became less than 0.01 MPa/strain increment. At this point, both axial and confining stresses were altered so that an effective isotropic stress of 0.55MPa was applied on the sample (end of Stage 1). The sample was allowed to rest at this effective stress for 10 minutes to allow the sample to rebound. Next, Stage 2 was conducted using the same procedures as Stage 1, but with an effective confining stress of 0.55 MPa. Once the “failure” was observed, the stresses were altered to an effective stress of 1.03 MPa. Finally, Stage 3 was conducted after a 10 minute interval, following the same procedures as the previous two stages. Figure 4 shows the multistage test results from sample FS-M1 with each of the stages highlighted. A standard description of multistage triaxial testing can be found in Ho & Fredlund [21].

**Hydrate Formation**

For samples containing methane hydrate (HS-M1 and HS-M2), the temperature of the cell was reduced to 2−3°C after initial consolidation. These conditions were maintained for 12 hours before the pore pressure of the system was increased to 4.8 MPa by injecting methane gas into the pore space of the sample. During the pressure increase, an isotropic effective stress of 0.28 MPa was maintained on the sample by increasing the axial and confining stresses. Once the target pressure was reached, the system was closed off, with the pore pressure maintained by a 3.85L gas bottle. The formation of hydrate was monitored by observing sample temperature and pressure, with hydrate formation completed following the exothermic temperature increase and accompanying pressure decrease. Typically, a spike in temperature up to 1°C over the control temperature indicated the start of hydrate formation in the samples. Hydrate formation was also monitored by seismic wave transmission and X-Ray CT scanning. Once the pressures necessary for forming hydrate were applied, waves transmitted through the sample were measured periodically. Although very little wave energy could propagate through an initial partially water saturated sample, once hydrate formed in the sample, the quality of the measured waveforms
improved significantly. In both HS-M1 and HS-M2, hydrate began forming within minutes once the pressure and temperature was brought into the stability zone. Both samples were left at hydrate forming conditions for 24 hours prior to the commencement of multistage testing.

CT Scanning

CT scanning was conducted during all tests where the samples contained ice or hydrate. Images were taken: post initial consolidation prior to ice or hydrate formation; pre-multistage testing after ice or hydrate formation; and post multistage testing. The main aim of the CT scanning analysis was to determine the structure and distribution of the ice or hydrate within the sediment. This helps in the interpretation of the P- and S-wave velocities gained from seismic testing, and in the evaluation of the impact of any heterogeneity on the samples tested.

RESULTS

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma'$ (MPa)</th>
<th>Peak strength (MPa)</th>
<th>Water Sat (%)</th>
<th>Hydrate Sat (%)</th>
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<td>Sand S-M1</td>
<td>0.275</td>
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</tr>
<tr>
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<td>0.550</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td>1.034</td>
<td>5.40</td>
<td>21.1</td>
<td>-</td>
</tr>
<tr>
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<td>0.275</td>
<td>3.29</td>
<td>21.1</td>
<td>-</td>
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<tr>
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<td>0.550</td>
<td>4.44</td>
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<td></td>
<td>1.034</td>
<td>6.23</td>
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<td>-</td>
</tr>
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<tr>
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<td></td>
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<td>13.6</td>
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<td></td>
<td>1.034</td>
<td>7.81</td>
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<td>16.8</td>
</tr>
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<td>24.9</td>
<td>-</td>
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<tr>
<td>Kaolinite</td>
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<td>24.9</td>
<td>-</td>
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<tr>
<td></td>
<td>1.034</td>
<td>4.23</td>
<td>24.9</td>
<td>-</td>
</tr>
<tr>
<td>Sand and SSi-M1</td>
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<td>1.71</td>
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<td>-</td>
</tr>
<tr>
<td>Silica</td>
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<td>23.7</td>
<td>-</td>
</tr>
<tr>
<td>flour</td>
<td>1.034</td>
<td>5.27</td>
<td>23.7</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Peak strength results for multistage tests conducted on all samples.

Initial tests conducted in the GHGC focused on gaining compressional strength data for a number of sediment types including 100% F-110 silica sand (S-M1), 90% F-110 sand and 10% kaolinite by weight (SK-M1) and 90% F-110 sand and 10% silica flour by weight (SSi-M1). Figure 5 gives a plot of the multistage triaxial test results gained for each of these sediments. As these results are preliminary, only the stress-strain relationships for the samples tested will be plotted here rather than Mohr-Coloumb envelopes.

In Figure 5 it can be seen that the inclusion of fines into the F-110 sediment alters the stress-strain response of the sample. At 0.28 MPa effective stress, the addition of both kaolinite and silica flour decreases the strength of the F-110 sediment by the same degree. At 0.55 and 1.03 MPa effective stresses, the silica flour seems to have less of an effect on reducing the strength of the F-110 sediment, whereas the sand containing kaolinite shows a much lower peak strength at higher effective stresses.

Figure 5. Multistage plots for tests S-M1, SK-M1 and SSi-M1

The response of the sample containing kaolinite shows a larger reduction in strength due to the adverse interaction of the platy kaolinite particles and the F-110 sand grain contacts. Kaolinite particles sit between grain contacts and change the distribution of interparticle forces, thus reducing the strength of the material [22, 23]. This may also be occurring at the first load step for sample SSi-M1. The low effective stress results in silica flour particles sitting between sand grains and reducing...
the friction at sand grain contacts. The strength of sample SSI-M1 approaches that of sample S-M1 at higher effective stresses, because the compaction of the sediment may force the round silica flour particles away from sand grain contacts. It has also been shown that the inclusion of small diameter round particles to a large diameter sand can have a stabilizing effect when added in small fractions [24]. Another possible mechanism at work may be the effect of porosity changes caused by the inclusion of fines to a sand sediment. 10% by weight of kaolinite or silica flour to a fine grained sand will reduce the porosity of the bulk sediment but increase the porosity of the load bearing frame of the main sand fraction. The results shown in Figure 5 most likely show a combination of the effect of porosity change and the effect caused by the interference of fines on the sand grain particle contacts.

Results from Hydrate Tests

Results from dissociation analysis of the hydrate bearing samples suggest there was only 50% conversion of water to hydrate in samples HS-M1 and HS-M2, giving hydrate contents of approximately 14% and 17% respectively. CT scanning of the samples prior to multistage testing showed a relatively even distribution of hydrate formation across both samples (Figure 6).

Hydrate formation is observed in these CT scans as an increase in density. Therefore, hydrate formation can be monitored by examining subtracted images of scans before and after formation and identifying areas of increased density. The CT scans of samples HS-M1 and HS-M2 were made in 3mm slice increments giving 34 x-y cross section images over the length of the core. Figure 6 presents every other cross sectional x-y slice through each sample. For HS-M1 (Figure 6a) there was an increase in density across the core, with a slightly higher concentration seen in the top 6 slices. In HS-M2 (Figure 6b), there is also an increase in density over the length of the core indicating a fairly uniform hydrate distribution. It should be noted that there is a region in the central portion of sample HS-M2 where there the density does not increase. It can be interpreted that there may be less hydrate formation in this portion of the core and future interpretation of results must take this into account.

Triaxial test results for both hydrate tests are displayed in Figure 7. Unlike the non-hydrate bearing tests, peak strength was reached at much lower strains than the partially saturated and frozen sediments. For both samples at 0.28MPa starting effective stress, peak strength was reached after 2% strain had been applied to the samples, in

Figure 6. Images showing the change in density from CT scans before and after hydrate formation in (a) HS-M1 (14% hydrate) and (b) HS-M2 (17% hydrate).
comparison to 4% for other samples tested. This would indicate that hydrate is cementing the grains to create a more brittle material in both these samples [25].

Figure 7. Multistage plots of HS-M1 (14% Hydrate) and HS-M2 (17% Hydrate)

Although the total volume of the water initially mixed in the sand was the same, the different porosities of each sample (33% for HS-M1 and 30.1% for HS-M2) resulted in higher hydrate saturation in HS-M2 than HS-M1 (see Table1). As a result, hydrate in HS-M2 cemented sand grains more effectively than HS-M2. The effect of sediment porosity change and effective hydrate content was also evident when the samples were taken to failure.

Figure 8 shows the results from the CT scans taken after failure in samples HS-M1 (Figure 8a) and HS-M2 (Figure 8b). The scans are presented as x-z slices to give the length of the core in a single image. The different nature of the failure planes (dark blue to purple-colored lines) indicate HS-M2 exhibiting a single shear band. This implies HS-M2 may be more brittle than HS-M1 with two conjugate bands. The stress-strain relationships in Figure 7 also show that peak stresses at each testing stage occurred at slightly smaller strains for HS-M2, indicating more brittle behavior. As noted from Figure 6b, sample HS-M2 may have had a region of lower hydrate content in the central portion of the sample. By looking at the before and after failure CT scans, the shear band seen in Figure 8b cross cuts this region of lower density at a high angle signifying the failure of sample HS-M2 is indicative of the bulk properties of the hydrate bearing sand.

These results are in agreement with other published data on the strength of hydrate bearing sediments. Masui et al [12] reported on the increased strength of methane hydrate bearing sediments as hydrate saturation increased in the pore space. In addition, Grozic and Ghiassian [11] report that the mode of failure also changes with increased hydrate saturation in sands, noting that the angle of shearing resistance increases with increasing hydrate content.

Comparison of F-110 Results

Figure 9 compares the results from all the tests conducted on 100% F-110 sand samples. Plotted are the unfrozen sediment results, with 20% water saturation (S-M1); the frozen F-110 sand which contained a water saturation of 20% before freezing (FS-M1); and the hydrate bearing F-110 sample which was 20% water saturated before hydrate formation (HS-M1). All samples had an original porosity of approximately 33%. The figure shows that the inclusion of ice and hydrate...
into the pure F-110 sand pack increases the peak strength measured during the multistage test.

**Figure 9.** Multistage plots comparing results from tests conducted on F-110 sand samples S-M1 (20% water saturated), FS-M1 (20% Ice) and HS-M1 (14% Hydrate)

In Figure 9, the peak strengths of the hydrate bearing samples are slightly higher than those of ice at each load step. This difference is smaller than expected as the reported strength of pure methane hydrate is about 20 times stronger than that of pure ice [26]. If the water in both samples was 100% converted to ice (for FS-M1) and hydrate (for HS-M1), the latter sample should display a much higher strength than former. The similarity in the results is likely due to the reduced hydrate content in sample HS-M1 due to the 50% conversion of water to hydrate over 24hrs. Sample FS-M1 was kept frozen for 72hrs prior to triaxial testing, and thus we assume that nearly all water in the sample was converted to ice.

The multistage test conducted on sample FS-M1 shows that the frozen sand reached peak strength at similar strain rates to the unfrozen sand sample. This would indicate that ice behaves as a ductile material during loading at the strain rates used in this test due to ice creep [27, 28]. In contrast, the multistage results of the methane hydrate test HS-M1 shows the sample reaching peak strength at low strains at each load step. Hydrate cementation therefore creates a brittle sediment when compared to a purely frozen sand under the same strain rates. Hydrate therefore does not show the same creep behavior as ice under these loading conditions.

**Results from Seismic Measurements**

Compressional waves were measured during both hydrate tests HS-M1 and HS-M2. Although shear (torsion) waves were also measured, the data was found to be inaccurate due to errors in data acquisition and recording. A marked increase in amplitude of the received signal was observed in both waveforms from pre- to post-hydrate formation. Data was additionally collected as both samples were compressed to failure at the end of stage 3 in each multistage triaxial test. In order to observe the change in geophysical response, waveforms were recorded during dissociation of the hydrate.

**Figure 10.** Changes in the compressional waveforms during dissociation of sample HS-M1, plotted by time from the start of dissociation on the right vertical axis. Sample is maintained under 0.7MPa effective stress throughout the dissociation process. Note that the arrival of small wavelet near 0.15 ms is possibly the wave propagating through the vessel wall and the confining fluid.
Hydrate was dissociated within samples HS-M1 and HS-M2 by increasing the temperature of the system at a rate of approximately 2°C/hr. Figure 10 shows the compressional waveforms collected during the dissociation in sample HS-M1. Dissociation and the resulting changes in the waveform began to occur as the temperature of the system approached the stability zone boundary, approximately 60min after the temperature started to increase. The amplitude of the received waveforms decreased significantly as hydrate dissociated in the sample.

One difficulty in determining the P-wave velocity from the measured compressional waves, is that the measured wave velocity does not necessarily gives P-wave velocity due to the long wavelength of the measured waves. This problem can be solved if the measured compressional waves can be interpreted as “bar waves”. If gas was used as the confining fluid, interpretation of the “bar waves” would yield the Young’s modulus of the sample. It should be noted however, that a comparison of compressional waves from both liquid (water) and gas (air) confining fluids resulted in little differences in the waveforms. This may indicate that the velocities of the compressional waves measured for the hydrate bearing sediments can be used to determine the Young’s modulus of the samples directly. This result can be combined to determine the P-wave velocity once the S-wave velocity is determined from torsion wave measurements. The accuracy and limitations of such an approach will be investigated further in the future.

Future Applications of Gas Hydrate Geomechanical Cell

The preliminary results shown in this paper highlight the capabilities of the GHGC to measure a number of physical properties during hydrate formation in porous media. The ability to conduct both geophysical and geomechanical measurements concurrently provides detailed knowledge of how the mechanical properties of gas hydrate bearing sediments evolves over time when subjected to compressional loading. Further, the heterogeneity of the sample, both preexisting in the sediment and developing as a result of hydrate formation, can be imaged via X-Ray CT, which can be correlated to the of the results of the experiment.

Points of interest that have been highlighted by these initial tests have been the response of hydrate bearing sediments to strain rate under axial compression. The future testing regime planned for this apparatus includes a deeper investigation into hydrate saturation effects on the strength and failure modes of hydrate bearing sediments, as well as looking at different sediment types and their response to compression with various hydrate saturations. It is also hoped that the nature of sediment failure during hydrate dissociation can also be explored, with results from such tests expected to have direct implications on future exploitation of gas hydrate reservoirs.

Finally, the GHGC is also well suited for examining time-dependent changes in the geomechanical and geophysical (seismic) properties of sediments containing non-hydrate cements. For example, this device is readily applicable to the study of the properties of frozen sediments such as permafrost, and may be expected to have applications for research in that field.

REFERENCES


