Gas hydrate dissociation structures in submarine slopes

Iain Gidley and Jocelyn L.H. Grozic
Department of Civil Engineering – University of Calgary, Calgary, Alberta, Canada

ABSTRACT
Perpetrations to the thermodynamic equilibrium of hydrate-laden sediments can induce gas hydrate dissociation and result in the release of large quantities water and methane gas. Depending on the surrounding sediments, the produced gas and water will cause increased pore pressures, volumetric expansion, and/or fluid escape structures all of which have the effect of reducing the soil stability. This paper examines the results from laboratory tests performed using a physical, small-scale model of submarine soils with hydrate inclusions. The soils are modeled using Laponite, synthetic clay which swells to produce a clear, colorless thixotropic gel when dispersed in water. Hydrate inclusions in the form of layers and nodules are created from R-11 refrigerant, which forms hydrate structures at low temperatures and atmospheric pressures. R-11 hydrates have been shown to have similar structural properties to naturally occurring methane hydrates. The objective of the experimental program is to observe the path of the fluid escape structures and the subsequent slip plane that develops due to dissociation of the R-11 hydrate. The slopes are examined using high speed, high resolution imaging. By varying the hydrate placement, and the inclination of the slope, information on the stability in a variety of conditions can be garnered.

RÉSUMÉ
Perpétrations à l'équilibre thermodynamique de sédiments chargés d'hydrates peuvent induire la dissociation des hydrates gazeux et libérer de larges quantités d'eau et de méthane gazeux. Cette eau et ce gaz ainsi produits provoqueront, en fonction des sédiments environnants, une augmentation de pression des pores, une expansion volumétrique, et/ou un fluide permettant aux gaz de s'échapper, ce qui a pour effet de diminuer la stabilité du sol. Ce papier analyse les résultats des tests en laboratoire, tests utilisant un modèle physique à petite échelle de sols sous-marins avec inclusions d'hydrate. Les sols sont modélisés par la Laponite, une argile synthétique qui enfle dans l'eau et produit alors un gel thixotropic incolore et clair. Les inclusions d'hydrate disposées en strates et en nodules sont créées à partir d'un réfrigérant synthétique (R-11) d'hydrates. Il a été démontré que les hydrates R-11 ont des propriétés structurelles similaires à celles qui se produisent naturellement pour les hydrates de méthane. L'objectif de cette expérimentation est d'observer le chemin suivi par le fluide permettant aux gaz de s'échapper et le plan de glissement qui s'ensuit dû a la dissociation des hydrates R-11. Ces glissements sont observés par une caméra à haute vitesse et haute résolution.

1. INTRODUCTION

Gas hydrates are ice like compounds that form under conditions of high pressure and low temperature and thus can be found below the deep permafrost of the high artic and along the continental margins. Changes in pressure or temperature can cause the hydrates to become unstable and release large amounts of gas, which can result in destabilization of the surrounding soil.

Natural gas contained in the form of gas hydrates is of interest because of its potential as an energy resource, a global warming agent and a submarine geohazard (Kvenvolden & Smith, 1999). Kvenvolden (1999) also states that the submarine geohazard associated with gas hydrates is the most pressing societal concern.

In marine environments gas hydrates are found in the sediments beneath the outer continental slopes and margins where dissociation can have the effect of reducing the seafloor stability and increasing the potential for gas blowouts. Gas hydrates have been linked to several submarine slope failures. Perhaps the most extensively studied of these is the Norwegian continental margin where Jung & Vogt (2004), Mienert et al. (2005), Sultan et al. (2004) Sultan, Cochonat, Foucher, & Mienert (2004), Vogt & Jung (2002) have suggested that gas hydrate dissociation may have triggered one or more large submarine slides in this area. They theorize that thermal warming and increased deposition resulted in destabilization of the hydrates, which can be seen intersecting the slide scar areas. Field & Barber (1993) postulated that hydrate dissociation weakened the sediments of the Humbolt Slide Zone (Northern California continental margin), which resulted in a large retrogressive failure ultimately triggered by a seismic event. Extensive erosion is cited as the hydrate destabilizing mechanism leading to considerable local slumping on the New Jersey Margin (Haq, 1998). The well studied Blake Ridge hydrates are thought to be the cause of a large seafloor depression as documented by Dillon et al. (1998) and Booth, Winters, & Dillon (1994), W. P. Dillon et al. (1998). Although circumstantial evidence indicates that gas hydrates may play a role in submarine slope failures, our understanding of mechanics of the failures is still limited. To this end, a program has been developed examining the effect of gas hydrate dissociation and the resulting escape structures on submarine soils. The investigation is carried out using small scale physical and computer modeling.

1.1 Gas Hydrate Properties

Gas hydrates are a form of clathrate; compounds that occur when a molecule enters within the crystal lattice of another molecule (Merriam Webster, 2007). Gas hydrates are typically formed when methane becomes encapsulated within a water lattice. Heavier carbon gases such as ethane, butane and propane can also form hydrates, but are considerably less common than methane (A. V. Milkov, Sassen, Novikova, & Mikhailov, 2000).

Gas hydrates form in the presence of free methane, high pressure, and low temperature. These conditions can be found below deep permafrost and along the continental margin. Areas where gas hydrates are stable are referred to as the gas hydrate stability zone (GHSZ). The worldwide locations of gas hydrates can be seen in Figure 1. The GHSZ for marine gas hydrates is shown in Figure 2.

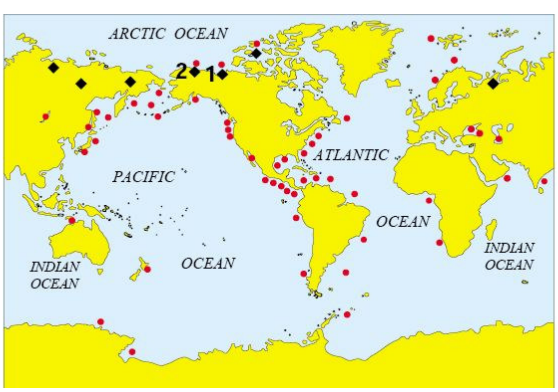

Figure 1: Worldwide locations of gas hydrates (U.S. Geological Survey, March 2001)

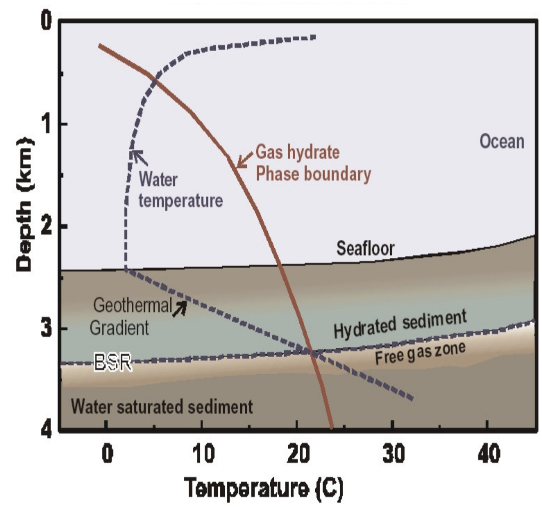

Figure 2: Stability zone for oceanic gas hydrates (Hyndman & Dallimore, 2001)

Gas hydrates contain an immense amount of gas. For example one cubic meter of hydrate will yield 0.8 cubic meters of water and 164 cubic meters of methane at standard pressure and temperatures (Carstens, 2004). The global amount of carbon contained within methane clathrates is estimated at 5 to 25 x 10^{14} kg (A. V. Milkov, 2004). For ease of comparison, the quantity of natural gas held in hydrate form globally is in excess of twice all the known conventional reserves (oil, gas, and coal deposits) with over 98% located in marine sediments (Kvenvolden, 1988).

1.2 Formation and Dissociation of Gas Hydrates

When gas hydrates are formed, water and gas are extracted from the surrounding pore space causing an increase in the shear strength as well as a decrease in the porosity, permeability and pore volume of the surrounding soil mass. The resulting soil structure will exhibit properties similar to ice, creating a more stable environment (Paull, Ussler III, & Dillon, 2000).

If the formation of gas hydrates causes a more stable environment, it stands to reason that the dissociation of gas hydrates creates a less stable environment. Perpetrations to the thermodynamic equilibrium can cause the once stable gas hydrate to dissociate. The result is an increase in porosity and permeability along with the development of gas bubbles and excess pore pressures, all of which decrease the shear strength of the surround soil mass (Judd, 1995; Paull et al., 2000).

2. GAS HYDRATES AND SLOPE STABILITY

The dissociation of gas hydrates causes an increase in the pore pressures of the surround sediment resulting in a weakening of the sediment.

The excess pore pressures can also lead to submarine slope failures in shallow water environments. They can also lead to the formation of vertical paths of gas migration and cause the failure of soil layers that are trapped by low permeability barriers (Xu & Germanovich, 2006). The slope failures can occur on slopes that would not fail according to a classical stability analysis. It has been suggested by Booth et al. (1994) that these gentle slopes should be investigated post failure to determine if: 1) hydrates are present in large quantities; 2) the slide scar intersects hydrate boundaries; and 3) low permeability soil or hydrate cap exists to facilitate the build-up of pore pressures. The presence of these indicators does not guarantee that hydrates are responsible for the failure but lends strong indications that they played a role. The main triggers for hydrate dissociation relate to a pressure or a temperature change. The following are common processes that will cause a change in the gas hydrate stability zone (W. P. Dillon & Max, 2003; Grozic, 2003; J. Mienert, Posewang, & Baumann, 1998; Paull et al., 2000).

- Pressure changes
  - Sediment deposition/erosion
  - Sea level rise/drop
  - Falling objects
  - Localized slumping, excavations
- Temperature changes
  - Global warming/cooling
  - Sea current temperature change
  - Anthropogenic activities such as heat from production wells
- Earthquakes
- Sediment salinity changes

3. TESTING PROGRAM

The testing program consists of two arms of research. The first being laboratory testing conducted using a small scale physical model of a submarine slope. The second is modeling the same small scale model using a finite element modeling program. Detailed information regarding the laboratory testing can be found in (Gidley & Grozic, 2008).

3.1 Laboratory Testing

A small scale, physical model of a submarine slope was constructed to facilitate testing the relationship between gas hydrate dissociation and the surrounding soil mass. The slopes were built using materials that simulate the in-situ conditions, while allowing for flexibility in testing and monitoring. The slopes were created from synthetic clay called Laponite and the hydrates were formed from R-11 refrigerant.

3.1.2 Materials

3.1.2.1 Laponite Clay

Laponite is synthetic clay, when introduced to distilled water, forms a clear, colourless, thrixotropic gel (Figure 3), that exhibits similar properties to clays commonly found in marine environments, synonymous with gas hydrates. The remolded shear strength was found to be 280 Pa at the conclusion of testing. The viscosity drops 10-15% due to temperature increases during a test. This was determined by converting viscometer readings from MacNeill (2007), to remolded shear strength using the method outlined in Locat & Demers (1988). The remolded friction angle was found to be 7.5 degrees from the angle of repose of the failed soil. Laponite is completely clear and colourless; this allows the bubble production and resulting gas escape structure from the hydrate to be observed in real time. It also facilitates the ability to monitor the test using high speed photography and video.

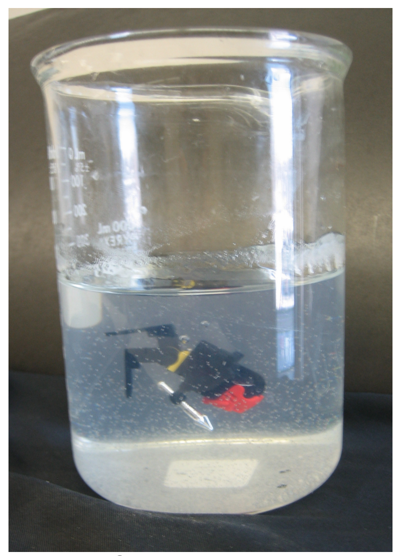

Figure 3: Clear Laponite clay

3.1.2.2 R-11 (Trichlorofluoromethane) Hydrate

Methane is the most common form of natural occurring hydrates (Wellsbury & Parkes, 2003). However, to form methane hydrates, considerable pressure and low temperatures would be required; thus making it difficult to obtain repeatable results. Also the storage and use of methane is a concern from a safety and ease of use perspective. These factors led to R-11 being selected to form hydrates. R-11 hydrates are stable at atmospheric pressures and temperatures commonly found in standard freezers.

3.1.2 Monitoring

The small scale tests were monitored for temperature and slope changes as well as structural changes, which were captured by high speed cameras.

3.2 Computer Modeling

The computer modeling component of the research program is currently in its preliminary stage. A finite element software package (Sigma /w) is used to perform stress-deformation analysis to compare hydrate theory with the laboratory results. A model slope was constructed (Figure 4) and the dissociation of the hydrates is represented by application of representative pressures in the hydrate cavity. From the analysis, a deformation map can be generated and compared to the laboratory observations. Then the stresses from the FE analysis can then be used as the initial conditions for a limit equilibrium slope analysis program (Slope /w), which can evaluate the probable slip plane for the given test set up.

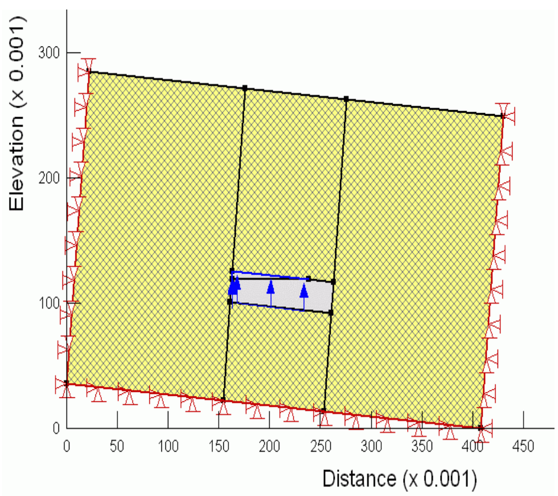

Figure 4: Sigma stress-deformation analysis set up

4. RESULTS AND DISCUSSION

4.1 Laboratory Testing

The laboratory testing investigated the effects of slope angle and depth of burial of the hydrate on the resulting gas escape structure and slope stability.

4.1.1 Sequence of Events

As the hydrate temperature warms, dissociation is initiated causing some of the refrigerant to turn to gas. As the dissociation process continues, the initial space occupied by the hydrate inclusion turns into a cavity filled with hydrate, water, refrigerant and gas (Figure 5). As more of the refrigerant becomes gas, the gas bubbles begin to coalesce on the upslope side of the hydrate cavity; this marks the beginning of the formation of the escape structure. The hydrate continues to warm and more and more gas is produced leading to the formation of a narrower, tubular escape structure (Figure 6). Finally this culminates into a full escape structure that vents to the atmosphere (Figure 7). Once the escape structure has fully formed the gas production increases dramatically. This indicates that the pressure build up necessary to overcome the overburden stress of the clay is enough to suppress dissociation of the hydrate.

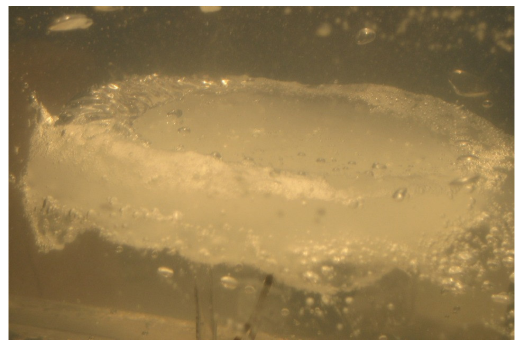

Figure 5: Initial gas formation

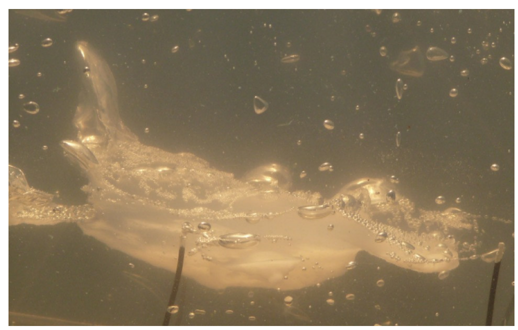

Figure 6: Early gas escape structure formation

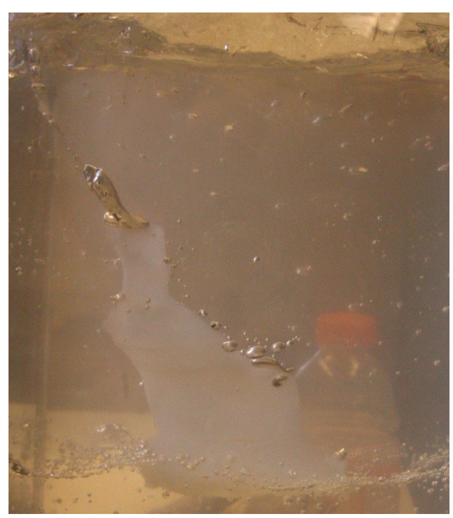

Figure 7: Fully formed gas escape structure

4.1.2 Effect of Slope Angle

The three different slope angles selected to be examined were 5, 10 and 15 degrees. They were selected to represent a slope angle less than, close to and above the angle of failure for the material. These slope angles also are very similar to the slope angles that are found on the continental margins where hydrates and hydrate related slides are common (McAdoo, Pratson, & Orange, 2000).

By changing the slope angle of the tests, the soil was being moved closer to and beyond its failure angle. At slope angles well below the failure angle, the initial escape structure would form on the upslope side of the hydrate. This occurs because the produced gas gathers at the top of the hydrate, and since the hydrate is tilted, parallel to the slope, the escape structure will grow from the upslope side of the hydrate due to buoyancy. The resulting escape structure grows almost vertical (Figure 8). As the slope angle approaches the failure angle of the soil, the initial escape structure begins to trend upslope (Figure 9). This seems to indicate that as the soil nears failure there is a plane of weakness forming within the slope. The results of the tests seem to indicate that the pressurization of the cavity can have a significant influence on the location of the failure plane within the soil. As the slope angle is increased beyond the failure angle (Figure 10), the final escape structure is similar to what is seen when the slope is near failure (Figure 9).

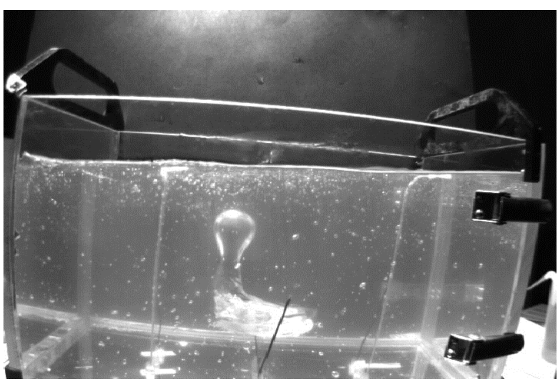

Figure 8: Bubble before release under a 7 inch burial at a 5 degree slope angle

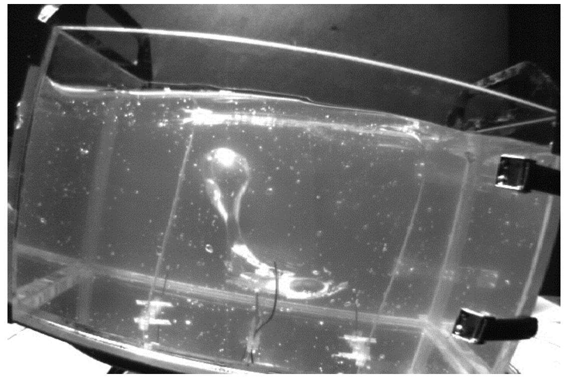

Figure 9: Bubble before release under a 7 inch burial at a 10 degree slope angle

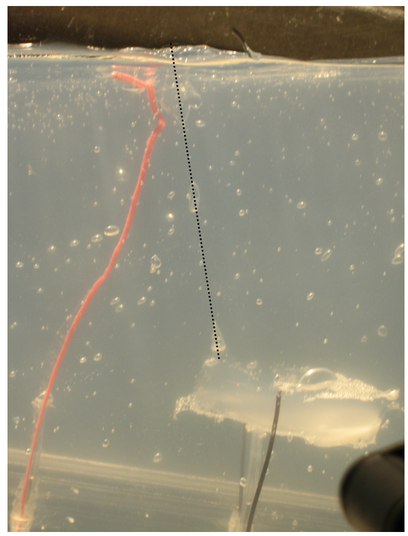

Figure 10: Bubble before release under a 7 inch burial at a 15 degree slope angle

4.1.3 Effect of Overburden

Gas hydrates can be found anywhere within the GHSZ. This means that hydrates can be very close to the surface, hundreds of meters below or throughout the entire sediment layer. The distribution of hydrates relies on a myriad of factors, gas supply, supply of free water, permeability of the soil, composition of the pore fluids, salinity and many others (De Batist et al., 2002; Field & Barber, 1993; Majorowicz & Osadetz, 2001).

During the laboratory testing the depth of burial was varied between 3, 5 and 7 inches. Also tests were performed with a hard crust located across the top of the sediments. The presence of a lower permeability, stiffer overburden layer is useful to simulate insitu conditions and also to examine the effect of significant depth of burial, beyond what could be simulated within the test apparatus. Figures 11 through 14 show the respective escape structures just before the escape structure breaches the surface. From these figures, and other similar tests performed, a few observations can be made. The figures suggest that there are three different levels of interaction occurring depending on the depth. For shallow burial, the data suggests that the escape structure is extremely sensitive to the orientation of the hydrate; the hydrate "tilt" will determine the orientation of the bubble growth and resulting escape structure. When the depth of burial is increased, it acts to reduce the sensitivity of the bubble growth to slight changes in the orientation of the hydrate. The dominant initial bubble growth trends upslope from the hydrate. Once the escape structure reaches a level where the gas pressure is high enough to overcome the overburden stress, buoyancy takes over and the bubble will explode through to the surface. The strength of the release of the gas is affected by the depth of burial. The deeper the hydrate is buried, the higher the pressure required to escape the system. From the tests performed with a stiffer crust, it can be seen that considerable pressure is required to even begin forming an escape structure. The pressure is high enough that the bubble no longer grows with a continuous surface; instead the surface shows faceted growth. The final initial escape structure when growing under a crust, will almost reach the surface, thus limiting the violence of the release of the gas. The growth of the escape structure shows some influence of slope initially, trending upslope as the tests performed without a crust. However, as the escape structure grows it does not form a single tube like structure; instead it grows as a large structure that covers the entire width of the hydrate (Figure 14). The final path of escape is will travel through any weaknesses in the surface crust, such as a crack caused by heaving on the surface.

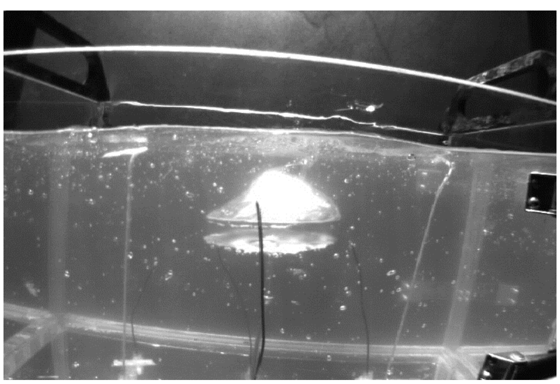

Figure 11: Bubble just before release under a 3 inch burial at a 5 degree slope angle

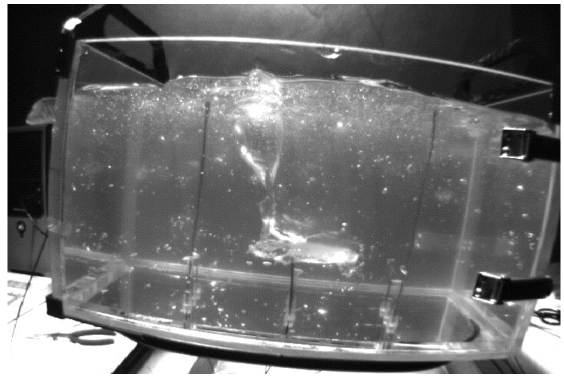

Figure 12: Bubble just before release under a 5 inch burial at a 5 degree slope angle

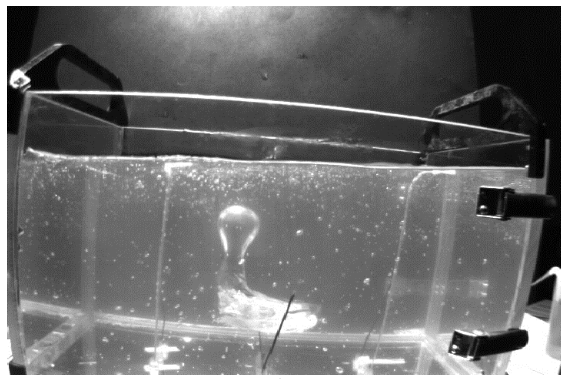

Figure 13: Bubble just before release under a 7 inch burial at a 5 degree slope angle

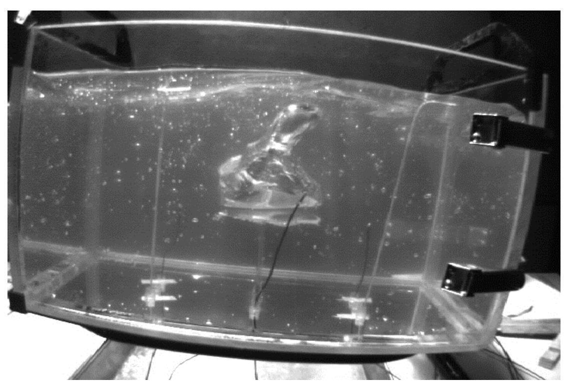

Figure 14: Bubble just before release under 5 inches burial with crust at a 5 degree slope angle

4.2 Computer Modeling

A finite element deformation-stress analysis is being used to model the deformation around the hydrate cavity, prior to the formation of the initial gas escape structure. Figure 15 shows the preliminary results from this process.

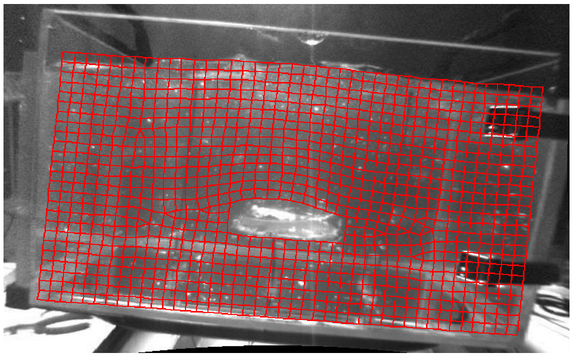

Figure 15: Deformation mesh superimposed upon pre escape structure photo

The resulting stress state is imported into a slope stability analysis program to locate the theoretical critical slip surface for the slope. Figure 16 shows the results from this process.

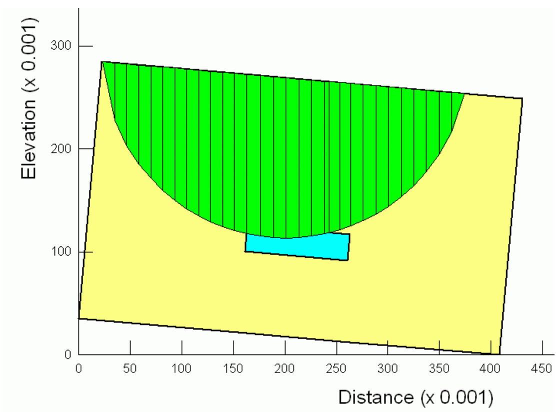

Figure 16: Critical slip surface from stress state in Figure 15

The initial results have been promising in matching observed slip planes, but are only in their preliminary stages.

5. FUTURE RESEARCH

Future work includes acquiring correlations between the physical and computer models. And investigating hydrate dissociation behavior under differing conditions such as the inclusion of hydrate sheets and multiple hydrate nodules.

6. CONCLUSIONS

Gas hydrates have been linked with several submarine slope failures ranging from small to catastrophic scale events. However, the overall role that gas hydrates played in those events is still in question. In this paper it has been shown that slope angle effects the direction of travel of the escaping gas. It has also been shown that depth of burial can affect the sensitivity to slope angle. Namely at shallower burials, there is limited influence of slope angle, but as the overburden increases, slope angle plays a larger role in the direction and severity of the escaping gas. These results compare favourably to geological investigations that have occurred in hydrate bearing sediments. Preliminary results from theoretical modeling have proved promising at mapping the deformations and stress states during testing but more research is needed to examine the applicability of the models. Future research will strengthen the link between the numerical and physical models and allow research into the size, shape and placement of the hydrates to occur.

7. ACKNOWLEDGEMENTS

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