GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Physical modelling of submarine gassy slope failures

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ABSTRACT
This paper investigates the stability of a submarine gassy slope triggered by tidal variations. Under tidal variations on an unsaturated slope, failure may occur under specific combinations of degree of saturation and soil permeability, and decreasing tidal period. A novel physical model test in a geotechnical centrifuge was undertaken of a submarine slope containing gassy sediments. The model preparation techniques, measurement systems and preliminary results are presented. The response observed in the model test is discussed and further developments proposed. Existing numerical simulations may provide a basis for verification and validation of future physical model test results.

RÉSUMÉ
Cet article étudie la stabilité d'une pente gazeuse sous-marine déclenchée par les variations des marées. Lors de la variations de la marée sur une pente non saturée, la rupture peut se produire dans différentes combinaisons de degrés de saturation, de perméabilités du sol et de diminutions de la période de la marée. Un nouveau test sur modèle physique a été réalisée à l'aide d'une centrifugeuse sur une pente sous-marine contenant des sédiments gazeux. Les techniques de préparation du modèle, les systèmes de mesure et les résultats préliminaires sont présentés dans cet article. Les observations et résultats obtenus dans l'essai y sont discutés et des développements supplémentaires sont proposés. Des simulations numériques existantes peuvent fournir une base pour la vérification et la validation des résultats futurs d'essai sur des modèles physiques.

1 INTRODUCTION

Submarine slope stability is an important concern and matter of research as offshore exploration becomes more prevalent and technologically advanced over the next few decades. Geohazards and associated ground movements in an offshore environment are a great threat to offshore infrastructure. Therefore the stability of a submarine slope is an important issue that must be taken into consideration during the design and operation of offshore facilities. The consequences of slope failure to oil and gas facilities would have a large financial, safety and regulatory impact. Moreover, submarine slope failures and tsunamis generated due to associated landslides near shore areas may cause considerable loss of life. The failure of a submarine slope might be initiated by a variety of potential triggering factors such as earthquakes, wave action, gas hydrate dissociation, tidal variation, sea level change, over steepening by erosion and minor slides, glaciations and volcanic activities (Locat and Lee 2002, Masson et al. 2006). Flow liquefaction in cohesionless sediments is a key source of submarine slope instability. Chillarige et al. (1997 a) mentioned that off the west coast of Canada submarine liquefaction flow slides occurred in deltaic sand and silts which contain gas and were mainly triggered by tidal drawdown. Wheeler (1990) noted a large number of seabeds around the world which contained gas bubbles at very shallow depth. Several case studies were presented by Chillarige et al. (1997 b) and Haththotuwa et al. (2011) on flow liquefaction of submarine gassy slopes triggered by tidal variation especially at low tides. Partially saturated seabeds of newly deposited Fraser River sands contain methane gas and possess susceptibility to flow liquefaction due to a time lag between tidal drawdown and pore pressure response as noted by Christian et al. (1997). Atigh et al. (2003) mentioned that reduction in pore pressure response with depth and time occurs from tidal variation on gassy seabed soil due to compressibility of pore fluid. Reduction of effective stress may lead to flow liquefaction of submarine slope because changes in pore pressure lag the reduction of seabed pressure changes during low tide. To model liquefaction flow of sand Atigh et al. (2004) developed an effective stress approach based on an elastic–plastic stress–strain relationship. To understand the behavior of both saturated and gassy deposits of loose Fraser River sand and Ottawa sand they used a fully coupled FLAC finite-difference analysis. Retrogressive flow slides were predicted from triggering of liquefaction for an unsaturated underwater slope similar to those observed near Sand Heads at the front of the Fraser River delta.

Geotechnical centrifuge testing is a well accepted physical modeling technique that has been used successfully to study various geotechnical engineering problems such as soil pipeline interaction and soil slope behavior using reduced scale physical models. A full scale soil structure is in equilibrium under earth's gravitational field g, similarly a reduced 1/100th scale model on a centrifuge under 100g will have stresses due to self-weight similar to the stresses in the full scale soil structure at homologous points. The model can then reproduce the phenomena of cracking, rupture or, flow that would be observed in the prototype because the stress dependency of soil behavior has been correctly simulated. The principles, scaling laws and some applications of centrifuge modelling are more fully described by Taylor et al. (1995) and Murff (1996).

Byrne (2003) designed a 1/50th scale physical model test of a gassy submarine slope failure for 50 g. The slope material was gassy loose sand with a dimension of 2H: 1V. For failure of this gassy slope a tidal range of 2.5 m was selected. Under tidal variations on an unsaturated slope, failure is expected to occur at a specific combination of degree of saturation, soil permeability and tidal period. For a specified degree of saturation and soil permeability, the possibility of failure increases with decreasing tidal period.

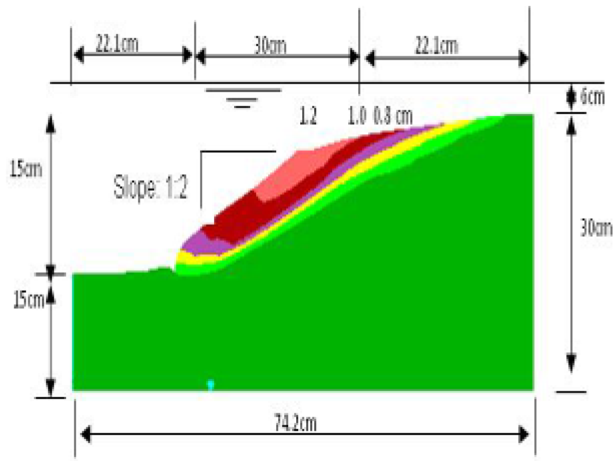

Figure 1 Predicted horizontal model movements

According to this design shown in Figure 1, a physical model test has been conducted in C-CORE centrifuge to investigate the stability of the submarine gassy slope under tidal variation by Kar and Phillips (2015). Appropriate model preparation techniques and control and measurements systems were developed for that test. Offshore soft sediments contain undissolved gas bubbles of carbon dioxide, hydrogen sulfide, ethane but mostly methane as noted by Esrig et al. (1977) & Jones et al. (1986). Ethylene was selected as the dissolved gas with water as the pore fluid to provide the necessary control of degree of sand saturation. Slope failure was not triggered in the first proof test of this setup under a wide range of tidal motions and gas pressures. The medium dense fine sand may not have been fully saturated with the gaseous pore fluid which may be the reason for no significant failure in that submarine gassy slope.

In this paper, authors mainly investigate the presence of gas in the pores of the soil slope and a suitable technique to measure the degree of saturation. Kar and Phillips (2015) introduced a soil moisture sensor VH400 to determine the degree of saturation of the soil sample. Some proof test results on sand columns will be presented in this paper.

2 SATURATION TECHNIQUE AND INSTRUMENTATION

2.1 Sand Column Material and Geometry

The sand column was made in a sealed steel cylinder of 19.8 cm diameter and 68 cm height. The sand used in the test was Alwhite #00, the same sand was used in centrifuge proof test. The cylinder is capable of holding a gauge pressure of 760 kPa and a vacuum of 30 in of Hg. A small layer of coarse sand was placed at the bottom of the column to distribute the fluid uniformly. A free space of 10.5 cm was at the top of the sand column. Figure 2 shows the geometry of the sand column.

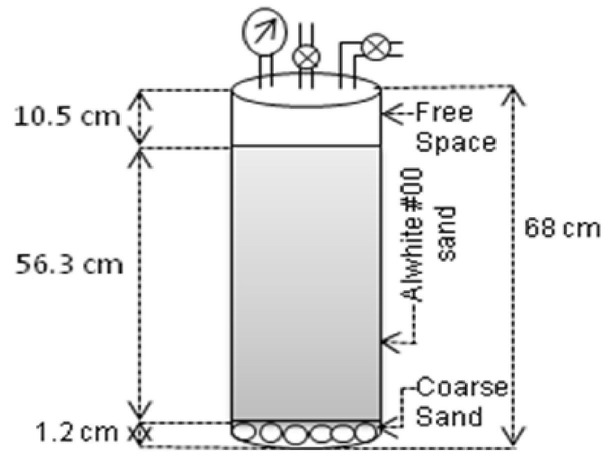

Figure 2 Sand column geometry.

2.2 Pore Fluid and Gas Selection and Saturation Process

To make the sand sample gassy, a large amount of gas was entrained in the pore fluid. In fresh water methane (CH_4) has a solubility coefficient of 0.034 L\L at 20°C, Yamamoto et al. (1976). To achieve the desired degree of saturation in the model, very high pressure would have to be used because of the solubility coefficient of methane. The solubility coefficient of carbon dioxide (CO_2) is 0.86 L\L in fresh water and stronger gas exsolution and expansion occurs as the gas is more soluble as explained by Red et al. (1994). Amaratunga et al. (2009) show that under a pressure gradient carbon dioxide (CO_2) cannot provide a controllable degree of saturation because of its high solubility. For a controllable degree of saturation ethylene, krypton and xenon are suitable choices and industrially available. Krypton and xenon are very expensive as compared to ethylene.

In this research, ethylene was used as the pore fluid gas with a solubility coefficient of 0.15 L\L at 20°C (www.engineering toolbox.com). Figure 3 shows the saturation setup of ethylene gas with water pore fluid, after Waite et al. (2011). Distilled water was used as the pore fluid and deaired for a few days under a vacuum of 30 in of Hg. Ethylene gas was then mixed with water under a gauge pressure of 655 kPa. The container of ethylene and water was placed in a cold water tub to reduce the mixing temperature. This decrease of ethylene water mixture temperature increases the solubility of gas in the water to ensure better saturation. A peristaltic pump was used to circulate the water for better mixing in a closed system. The gas pressure decreased with the circulation of ethylene mixed water. When the pressure was stable the cylinder pressure was again increased back to 655 kPa. The pressure of ethylene water mixture decreased through several cycles following the same process until the gas pressure stayed at the starting pressure. The data from the ethylene water saturation operation is shown in Figure 4.

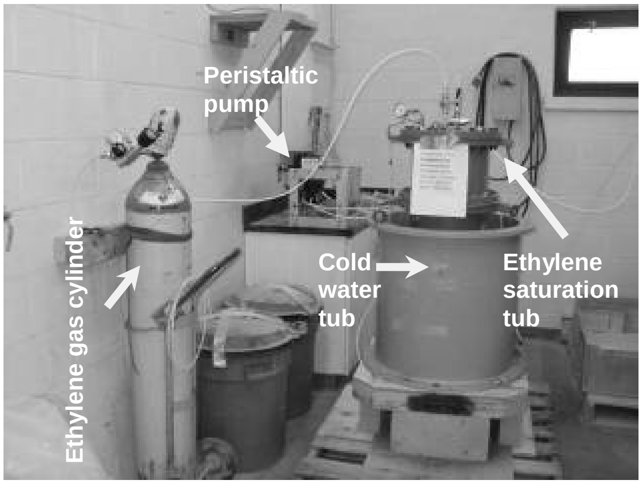

Figure 3 Lab setup of water saturation with ethylene.

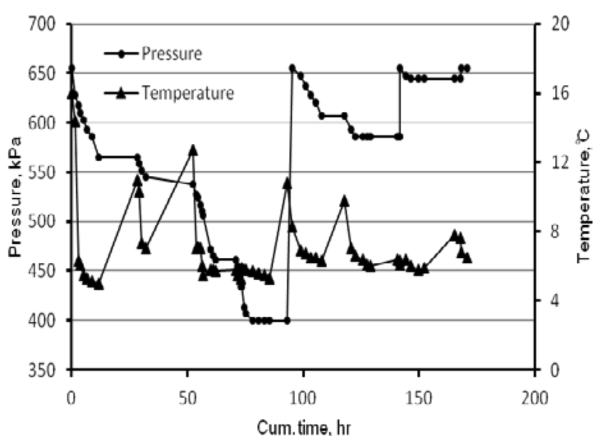

Figure 4 Gas pressure and temperature change with time.

2.3 Instrumentation

For measuring the degree of saturation of the sand column a soil moisture sensor was evaluated which determines moisture content. VH400 series soil moisture sensor is a very low power operational sensor with a probe length of 94 mm. This probe measures dielectric constant of soil using transmission line techniques. It is insensitive to water salinity, and does not corrode over time. A data acquisition channel (DAQ channel) was used to read and record data provided by the sensor. The output of this sensor is DC voltage proportional to the water content and it provides reading within a second. Figure 5 shows the orientation of the sensors in two soil columns in both horizontal and vertical direction

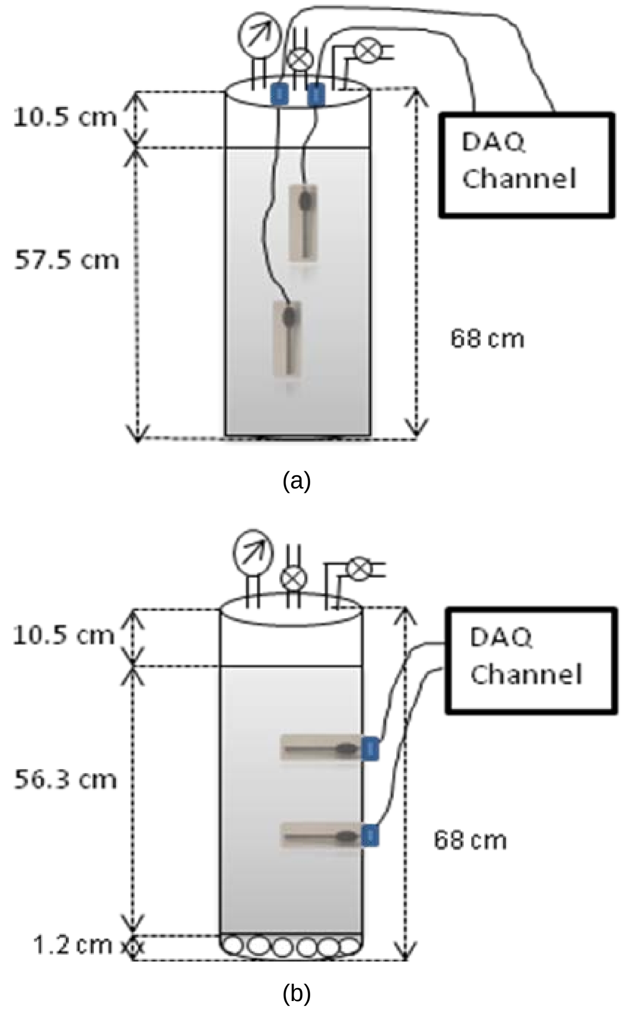

Figure 5 (a) Sensor in vertical direction. (b) Sensor in horizontal direction.

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3 TEST PROCEDURE

In the centrifuge model test, the slope was first saturated using distilled deaired water with a very low head to prevent piping after vacuum and carbon dioxide displacement of air. Carbon dioxide was used to replace the remaining air as the solubility coefficient of carbon dioxide in water is much higher than air. Then the whole system including strong box and water container was brought to the same pressure as ethylene mixed water. Ethylene mixed water was then passed through the slope in the strong box displacing the distilled deaired water into the water container. Figure 6 shows the lab setup for centrifuge model test preparation.

This same process of sample preparation was followed to make the sand column samples. Centrifuge strongbox was replaced by a sand column for simplicity. Dry sand was poured into the sand column and deaired under vacuum. The same flushing process was applied a couple of times.

Figure 6 Lab setup for centrifuge model test preparation

Distilled deaired water then flushed through the sand column with a very low head. Biggar et al. (1960) noted that the water flow velocity can vary between 0.30 cm/hr and 2.49 cm/hr for a sand grading like Alwhite #00 during inundation. In these tests, the initial flow velocity was 1.77 cm/hr and decreased to 0.49 cm/hr to 0.84 cm/hr during inundation. The initial flow velocity was higher because of the coarse grain layer. Figure 7 shows the whole setup for the sand column test.
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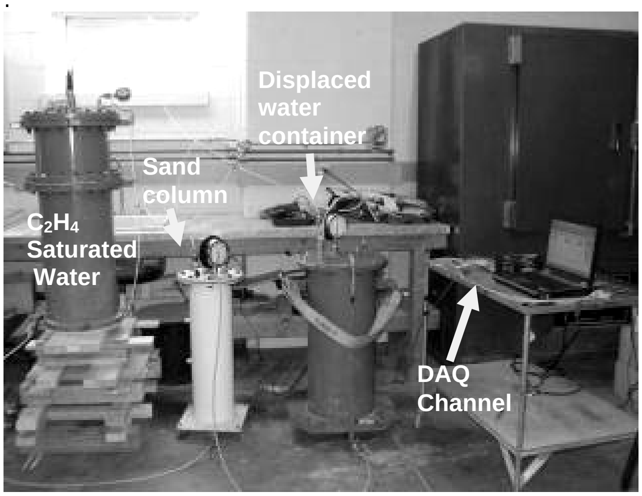


Figure 7 Lab setup of sand column test

After saturating with deaired water under vacuum, the pressure in the cylinder was brought to 655 kPa which is the same pressure as the ethylene saturated water container. Ethylene saturated water was passed through the sand column under a very low driving head. This ethylene saturated water displaced the water in the sand column. Ethylene saturated water was flushed up to 1.7 times of sand column pore volume to ensure the presence of gas in the sand column sample. When the model was ready, the pressure was reduced in steps and the moisture sensors monitored. The required pressure drop was calculated using Equation 1 proposed by Henry and Boyle's, where H is the Henry's constant and for ethylene Henry's constant of 0.114982. S_r is the degree of saturation.

$$S_r = \frac{P_2 - P_1 . H}{P_2(1 - H)} \quad [1]$$

The sensor reading should change with pressure reduction because with decreasing pressure gas bubbles expand reducing the degree of saturation. Figure 8 shows another method for measuring the global degree of saturation. In this method, the amounts of water and gas released from the sand column while decreasing the pressure were measured. Two more sand columns were made following the same process as above, but without the soil moisture sensors. A gas vessel was used with a very low volume. Two pressure transducers were used to monitor the pressures in the sand column and the gas vessel. At constant temperature,

$$P_1 V_1 = P_2 V_2 \quad [2]$$

According to Boyles law Equation 2, the product of pressure and volume of a gas remains constant at constant temperature. In these tests while reducing the pressure some water and gas will be displaced from the sand column into the gas vessel. The degree of saturation can be assessed form the displaced water volume and the equilibrium gas pressure.

$$\mathbf{Sr} = \frac{\mathbf{P_2 - P_1 . H}}{\mathbf{P_2(1-H)}}$$

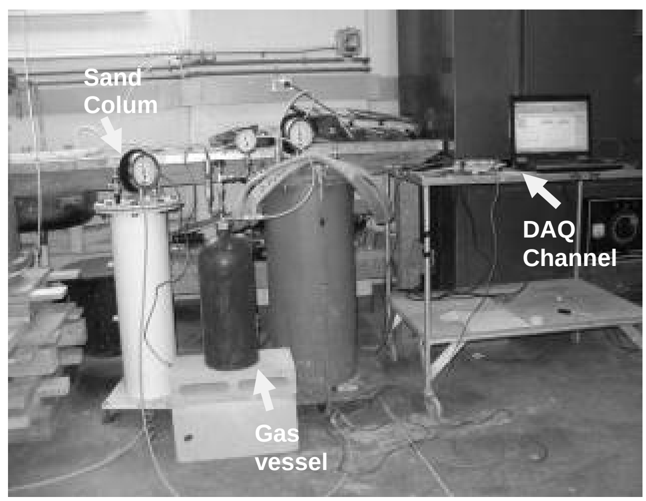


Figure 8 Lab setup for measuring global degree of saturation.

4 RESULTS

To determine the degree of saturation and ensure the presence of ethylene gas in the submarine gassy slope, sand column tests were done with soil moisture sensors following the process of ethylene saturation to ensure the presence of gas. Soil moisture sensors were placed in the sand column in either a horizontal or vertical orientation. The values obtained from soil moisture sensor in air and water are 0.0851, 2.957 and 0.08564, 2.971

volts for sensor 3 and sensor 2 respectively. While flushing with deaired distilled water, from Figure 9, the sensor reading changed with the change of the water level. Due to capillary rise soil moisture sensors start to respond while the distilled deaired water phreatic surface was below the sensor position. With the rise of distilled water level the degree of saturation increases at the sensor elevation. In all case soil moisture sensors show 100% saturation after they are immersed. Another test was done with the change of soil moisture sensor orientation with some coarse material at the soil base. The soil moisture sensors show the same behavior while the sensor was in horizontal direction.

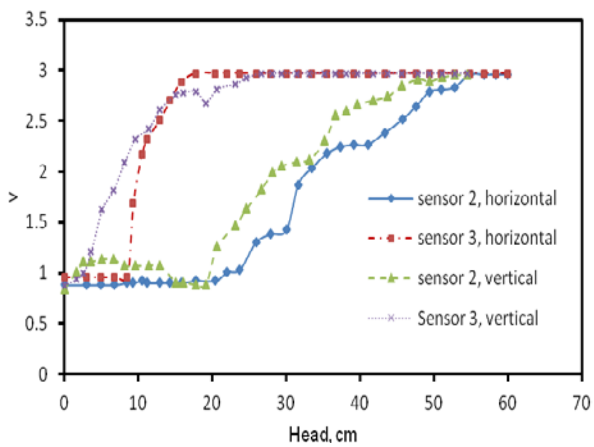


Figure 9 Soil moisture reading for both sensor orientations.

The ethylene saturated water filled sand column was pressurized to 655 kPa, with a degree of saturation of 1. To reduce the degree of saturation,the pressure of the sand column was gradually reduced. With the reduction of pressure, some gas comes out of solution and existing gas bubbles expand.

Holocher et al. (2003) shows time required for different gas diffusion in water, Figure 10. The time required for krypton and xenon gas bubbles diffusion in water is about 15 minutes. Diffusivity and solubility coefficient of Ethylene is same as Krypton. So, the time required for ethylene gas diffusion is assumed to be similar to krypton. Same diffusion time as Krypton was therefore allowed as a minium for dissolved gas to come out of solution.

The response of the soil moisture sensors in both orientations with decreasing pressure is presented in Figure 11. Soil moisture sensors do not show any changes in voltage with the sensors in a vertical orientation. Top sensor shows some change with decreasing pressure when sensor was in horizontal orientation.The bottom sensor however has no change in voltage.

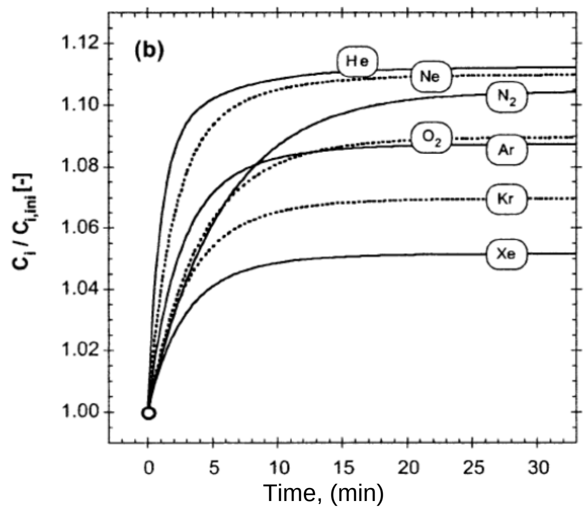


Figure 10 Estimated gas solution time, Holocher et al. (2003)

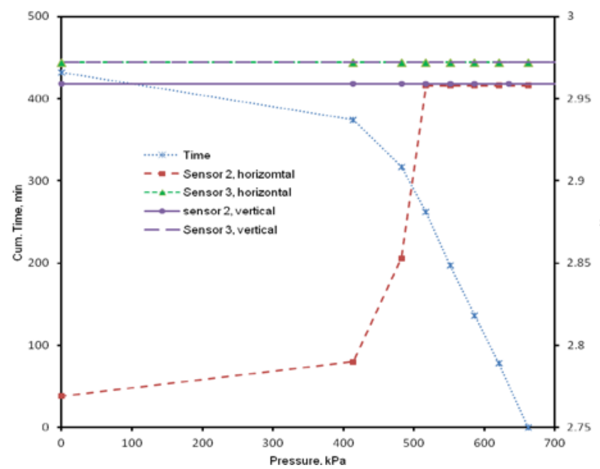


Figure 11 Sensor response to decreasing pressure

The top sensor change in voltage may mean with a decrease in pressure gas expansion occured around the sensor as the degree of saturarion decreased. A calibration of soil moisture sensor VH 400 was presented by Kar and Phillips (2015). Figure 12 shows this soil moisture sensor VH400 calibration in Alwhite 00 sand. The response from the sensor was not comparable with the expected degree of saturation. These moisture sensors did not provide a voltage correspondent to degree of saturation with decreasing pressure.

The data of the global degree of saturation tests are presented in Figure 13. The theoretical volume of gas released with decreasing pressure is based on equations 1 and 2. It is assumed that the gas pressures are the same throughout the system. In fact, gas pore pressures should always be slightly higher than the pore water pressures due to surface tension. The measured gas volumes from the 2 column tests are initially comparable to the expected values down to about 550kPa absolute pressure in both magnitude and trend, given the accurate of the volume measurements. This pressure gives a degree of saturation of about 90% or less. Below this pressure level, the released gas volume is only about half the theoretical value at a goven pressure level. The reason for this decrease is unclear. Below 85 to 90% saturation, gas bubbles in the sand pores merge to form a continuous gas phase and pathways for released pore gas to exit the sand sample. This change in gas transport may be factor in the observed behaviour.

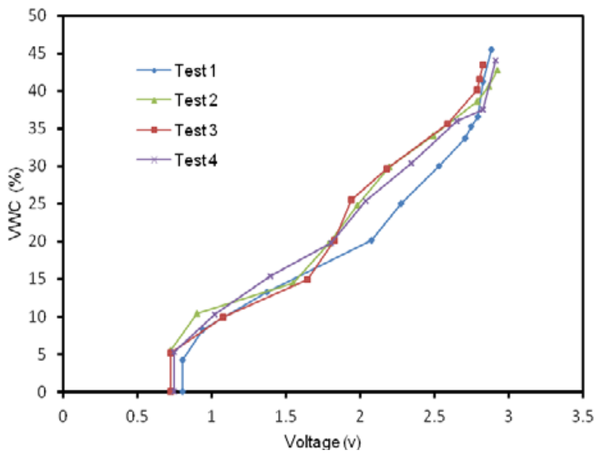


Figure 12 VH400 sensor calibration in Alwhite 00 sand Kar et al. (2015).

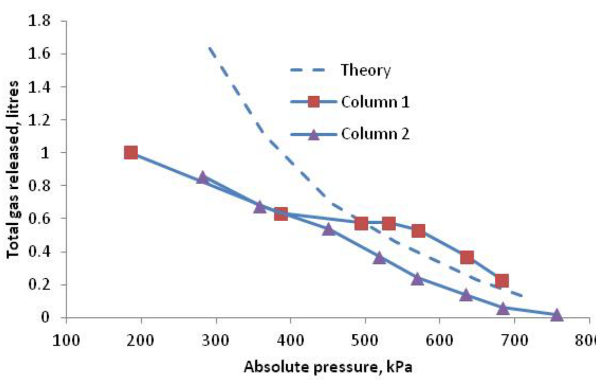
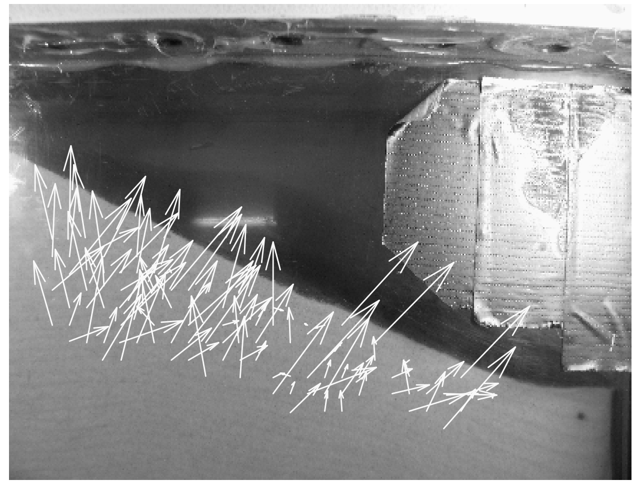


Figure 13 Released gas measurements

In the centrifuge model test, failure of submarine slope was expected to occur for specific combinations of degree of saturation, soil permeability and tide period. For a specified degree of saturation and soil permeability, possibility of failure increases as the tide period decrease. A slope failure was not triggered in the first proof test of this setup under a wide range of tidal motions and gas pressures. There was evidence of slight volumetric expansion from gas dissolution under 50g. Much more volumetric expansion was seen while stopping the centrifuge from 50g. Figure 14 a shows PIV analysis, which indicates the evidence of volumetric expansion due to the associated decrease in total stresses in the sand. The noise in the displacement vectors indicates the effects of expanding gas bubbles, as seen near the slope crest at 1g, Figure 14b, These gas bubbles expanded during the 45 minute period after swingdown. This volumetric expansion confirms the presence of some gas in the slope model.



(a)

(b)

Figure 14 (a & b) Volumetric expansion of slope after swing down.

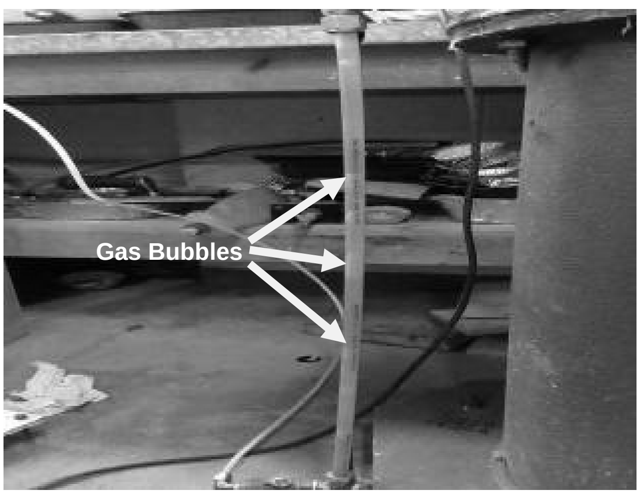
To better understand the presence of gas in the centrifuge slope mode, some experimental tests werte conducted to measure the degree of saturation of sand column. Figure 15a-c shows the presence of ethylene mixed water in the sand column. While decreasing the pressure, gas comes out of solution and the bubbles expand. A transparent standpipe was attached to the water column. Gas bubbles were also seen in that pipe during depressurization of the sand column. Excavation of the sand column after removing the cylinder lid also showed evidence of gas bubbles. There were also some bubbles around the top soil moisture sensor. Gas was therefore present throughout the column.

5 CONCLUSIONS

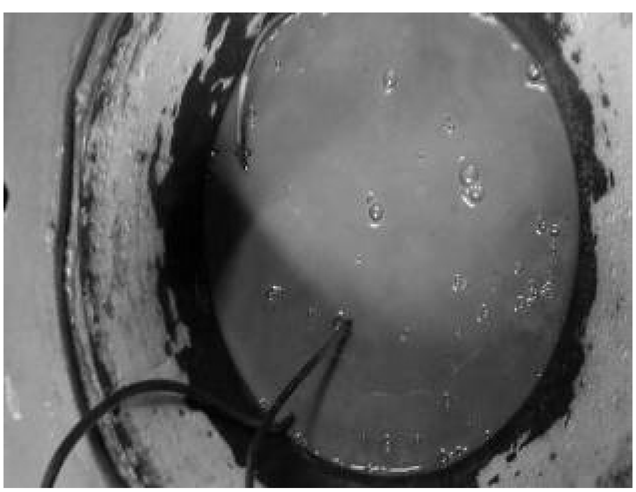
For investigating failure of a submarine gassy slope under tidal variation in the geotechnical centrifuge, some supporting lab tests have been done. Proposed ethylene saturation process has been applied on a sand column. Some evidence of gas exsolution and bubble expansion with depressurizationis are presented in this paper. This means ethylene gas was dissolved in the water and present in the soil pores. Soil moisture sensor VH400 shows good response while soil column was saturated with water. These soil moisture sensors do not work properly with decreasing pressure. A better method for determining degree of saturation will be developed for future submarine gassy slope tests.

6 ACKNOWLEDGEMENTS

The assistance of the geotechnical engineering team at C-CORE is much appreciated. The financial support of Chevron Canada Limited for the research, and Hibernia Management & Development Corporation for C-CORE centrifuge access for graduate students, is gratefully acknowledged.



(a)



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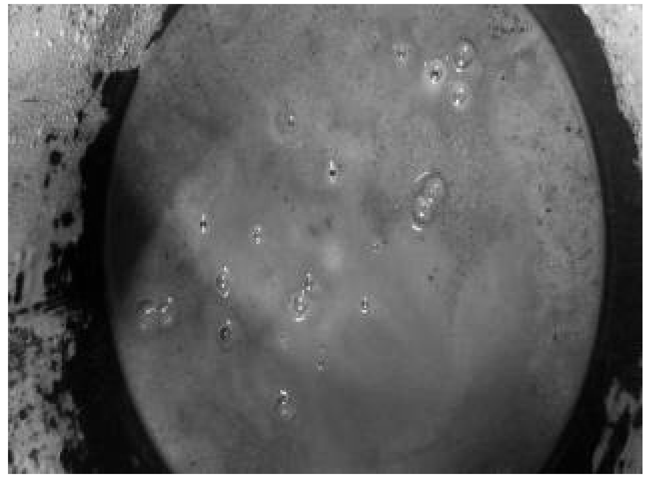

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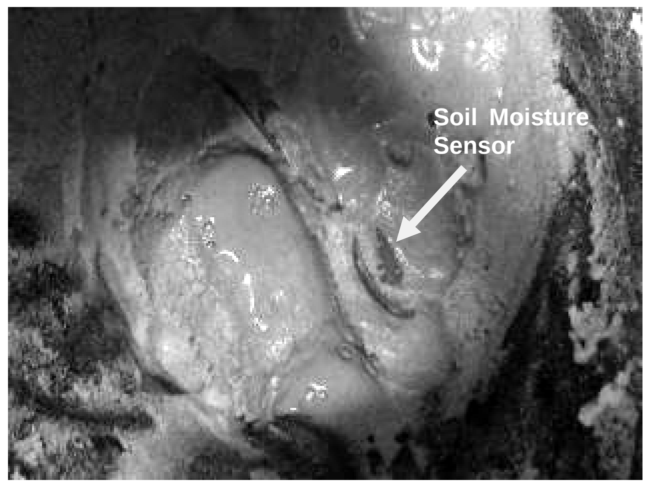

(d)

Figure 15 (a) Standpipe gas bubbles. (b & c) gas bubbles at vertical and horizontal position of sensors. (d) bubbles beside soil moisture sensor.

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