Evaluation of sample disturbance due to the exsolution of dissolved gas in the pore water of deep lake bottom sediments

Évaluation du remaniement des échantillons dû à l'exsolution de gaz dissous dans les eaux interstitielles des sédiments de fond de lacs profonds

Yamashita S., Miura R.
Kitami Institute of Technology, Kitami, Japan

Kataoka S.
Hakodate National College of Technology, Hakodate, Japan

ABSTRACT: Core samplings were conducted in the Lake Baikal, Russia, where shallow gas hydrates existed. To examine the mechanical properties of lake-bottom sediments, the handy vane shear and cone penetration tests were performed for the core samples on board. To evaluate the sample disturbance due to the exsolution of dissolved gas during sampling, the relations between the concentration of dissolved gas in the pore water and the strength were also examined. Moreover, laboratory tests which simulate the stress relief from bringing the samples to the lake surface were also performed. Test results showed that the strength of soils becomes lower with the increase in degree of gas concentration on both on-board and laboratory tests. It was also showed that the in-situ strength can be estimated roughly from the disturbed samples.

RÉSUMÉ : Un prélèvement d'échantillons stratigraphiquement représentatifs (carottes) a été mené dans le lac Baïkal, en Russie, où il existe des réservoirs d'hydrates de gaz peu profonds. Afin d'examiner les propriétés mécaniques des sédiments de fond de lac, on a procédé à des essais de cisaillement avec un scissomètre portatif et à un test de pénétration au cône sur ces échantillons stratigraphiquement représentatifs, ceci sur place. Dans le but d'évaluer le degré de remaniement des échantillons dû à l'exsolution de gaz dissous au cours du prélèvement, on a également examiné le lien entre la concentration de gaz dissous dans les eaux interstitielles et la résistance de l'échantillon. On a, en outre, procédé à des tests en laboratoire qui simulent le relâchement de contraintes résultant de l'apport des échantillons à la surface du lac. Les tests menés sur place tout comme ceux menés en laboratoire, indiquent que la résistance des sols diminue plus le degré de concentration en gaz augmente. Ils ont également démontré que l'on pouvait obtenir une estimation approximative de la résistance in situ du sol à partir de l'échantillon remanié.

KEYWORDS: dissolved gas, gas hydrate, sample disturbance, lake bottom sediment

1 INTRODUCTION

Gas hydrates (GH) are attracting attention as a next-generation energy source. In Japan, survey and test drilling of GH for resource development have been conducted in around the Nankai Trough. On the other hand, GH are also attracting attention in relation to the global environment, because methane gas contained in the GH has approximately 20 times the greenhouse effect of carbon dioxide. There are concerns that dissociation of GH and exsolution of dissolved gas, from the GH distributed in submarine surface layers, due to rising ocean temperatures or leakage at recovery of the hydrates for energy, may contribute to global warming. Moreover, these phenomena or seismic activities can reduce the stability of seabed and may induce seafloor landslides. Therefore, it is necessary to clarify the mechanical properties of the GH-bearing ground and the strength change of seabed sediments due to the dissociation or exsolution.

In generally, to assess the in-situ strength, laboratory tests on samples retrieved from the site or in-situ tests have been performed. However, it is difficult to perform the in-situ test in the deep lake or seabed. On the other hand, samples for laboratory tests taken from lake or seabed soils in deep waters are subjected to a large stress (back water pressure) relief. Even a small amount of gas dissolved in the pore water will come out of solution and cause disturbance to the soil structure due to the stress relief. As a result, laboratory tests may not give appropriate results for the in-situ soil conditions.

In this study, to evaluate the effects of the exsolution of dissolved gas in the pore water on the strength properties, core samplings were conducted in the Lake Baikal, Russia, shallow GH province, and some kinds of on-board tests were performed. Laboratory tests which simulate the stress relief from bringing the samples to the lake surface were also performed.

2. SURVER AND SOIL SAMPLING

The sampling of lake-bottom sediments contained GH were conducted in the Lake Baikal, Russia, September 2010, by the survey ship '*Vereshchagin*' of the Russian Limnological Institute. It is already reported that GH in the Lake Baikal is formed at immediately beneath lake-bottom of the mud volcano that is observed the eruption of cool spring water contained gases by the echo sounder (e.g., Matveeva et al. 2003). Thus, at locations where mud volcanoes were confirmed by the echo sounder images, lake-bottom sediments were collected by using a gravity core sampler (sampler length is about 5 m, diameter is 110 mm and weight is about 700 kg). Sampling sits are Novosibirsk site (water depth is about 1450 m) and Kukuy site (water depth is about 800 m) at the central parts of the lake, as shown in Figure 1. The lake-bottom sediments cores were retrieved 40 sample cores (24 cores in Novosibirsk site, 16 cores in Kukuy site).

After core samplings, these cores were cut into 1-m interval. Then, each section was cut up longitudinally on two parts for subsequent processing. To measure the strength of sediments immediately after recovery, the handy vane shear test (blade diameter is 10 mm, height is 20 mm; 10 to 40 cm interval) and cone penetration test (diameter is 9 mm, length is 16.8 mm, apex angle is 30 degrees; 10 to 40 cm interval) were performed on board. For measurement of the water content, 10 to 40 cm interval samples were taken. Additionally, the dissolved gases in the pore water were taken by the headspace gas method.

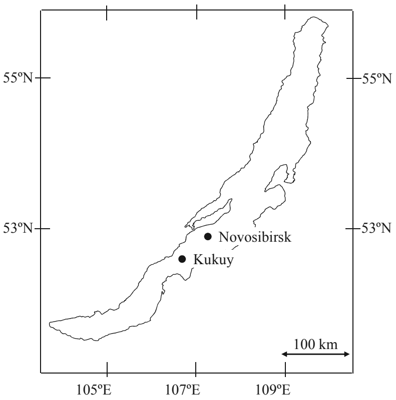

Figure 1. Survey and sampling sites in the Lake Baikal.

3 ON-BOARD TEST RESULTS

Figure 2 shows the on-board tests results (vane share strength, τ_v, and cone penetration resistance, q_c), together with the profiles of water content, w, with depth. In the samples retrieved from Novosibirsk site, the water contents in the upper strata of samples that were able to collect GH in lower part of the core (with GH) are lower than those of the samples that were not able to collect GH (without GH), and the strengths of samples with GH are higher than those of samples without GH, as shown in Figure 2(a). On the other hand, in the samples retrieved from Kukuy site, although the water contents of samples with GH are lower than those of samples without GH as same as Novosibirsk samples, the strengths are similar, as shown in Figure 2(b). Thus, the relations between the strength and the water content are different from the sampling site. The reason seems to be that the difference of degree of sample disturbance due to the exsolution of dissolved gas in the pore water caused by the decrease of pressure during the pulling up of core, because the concentrations of methane gas dissolving in pore water may be different from site. Then, the concentrations of methane gas dissolving in the pore water of sediments were measured, and the effects of the concentrations of gas on the strength of samples were examined.

Figure 3 shows the relations between the depth and the concentrations of dissolved methane gas, CH_4, per sediment of one liter (Hachikubo et al. 2010). In the case of Novosibirsk samples, the gas concentrations are high from surface layer, irrespective of with/without GH. On the other hand, in the case of Kukuy samples, although the gas concentrations of samples with GH are high from surface layer, those of samples without GH are low at surface layer and increase suddenly from a certain depth.

Figure 4 shows the relations between the vane shear strength, τ_v, and the water content, w. It is found that the difference of strengths in Novosibirsk samples is not recognized irrespective of with/without GH, as shown in Figure 4(a). It would seem that the degree of sample disturbance due to the exsolution of dissolved gas in the pore water are similar, because the gas concentrations are high from surface layer irrespective of cores, as shown in Figure 3(a). On the other hand, in Kukuy samples, the strengths of samples with GH are lower than those without GH. It would seem that this is because the gas concentrations of samples with GH are high from surface layer as shown in Figure 3(b), so that the sample disturbance due to the exsolution of dissolved gas became large, and the strength became low. Thus, the correlation between the strength and the water content is recognized, considering the sample disturbance due to the difference of the gas concentration. The similar test results were obtained on the sea-bottom sediments retrieved from offshore Sakhalin Island, Sea of Okhotsk (Yamashita et al. 2011).

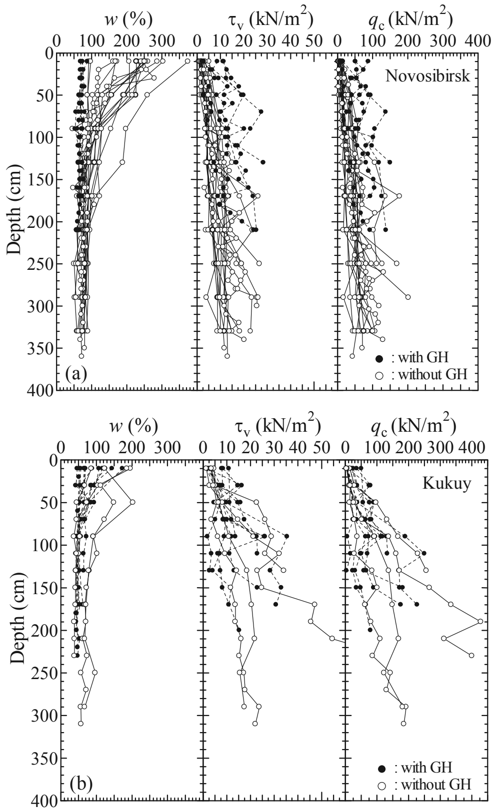

Figure 2. On-board test results; (a) Novosibirsk site, (b) Kukuy site.

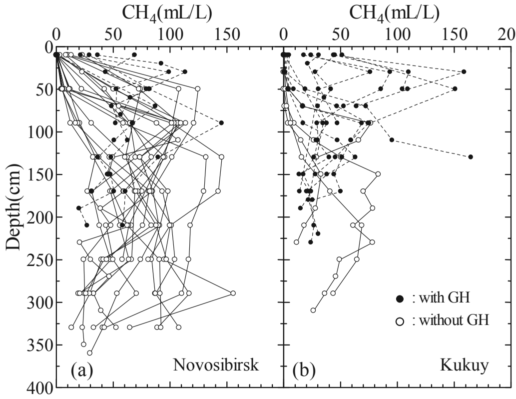

Figure 3. Concentration of methane gas with depth; (a) Novosibirsk site, (b) Kukuy site.

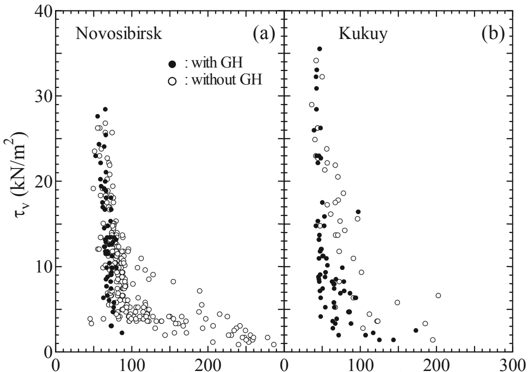

Figure 4. Relations of vane shear strength and water content; (a) Novosibirsk site, (b) Kukuy site.

4 LABORATORY TEST

From the on-board test results and the measurement of gas concentrations, it was guessed that the strength of samples retrieved from GH-bearing ground is decreased by the sample disturbance due to the exsolution of dissolved gas during the sampling. In order to clarify this, the strength change by the sample disturbance due to the exsolution of dissolved gas in the pore water was evaluated by the laboratory tests which simulate the stress relief from bringing the samples to the lake surface.

4.1 Test apparatus and test method

Figure 5 illustrates the oedometer apparatus using the simulating laboratory test. Used sample is a mixed Baikal lake-bottom sediment (ρ_s = 2.720 g/cm^3, w_L = 70.1 %, I_p = 41.9, clay content is 58 %, silt content is 40 %, sand content is 2 %) retrieved from the Kukuy site at 2005 and 2006 (Kataoka et al. 2009). The mixed sample is slurry state having an initial water content of 1.6 times the liquid limit. Used gas is carbon dioxide (CO_2) instead of methane (CH_4), because CO_2 gas has high solubility in comparison with CH_4 gas. For example, the solubility of CH_4 gas under water temperature of four degrees centigrade and water depth of 1000 m is almost same to that of CO_2 gas under water temperature of 20 degrees and back water pressure of 500 kPa.

The laboratory tests were conducted on three test conditions as shown in Table 1 and Figure 6. The consolidation time is 24 hours for each consolidation stage of 20, 50, and 100 kPa. The back pressure was applied after end of consolidation of 20 kPa. In the case of Test Case 1, the back pressure of 500 kPa was applied by air pressure. On the other hand, in the cases of Test Case 2 and 3, the back pressure was applied by CO_2 gas pressure. The back pressures of Case 2 and 3 were 100, 300 and 500 kPa, respectively. In the Case 1, deaired water was permeated through the sample after end of consolidation of 100 kPa. In the Case 2 and 3, CO_2 gas dissolved water was permeated. The permeated time is 10 days. The volume of permeated water is similar to the volume of sample.

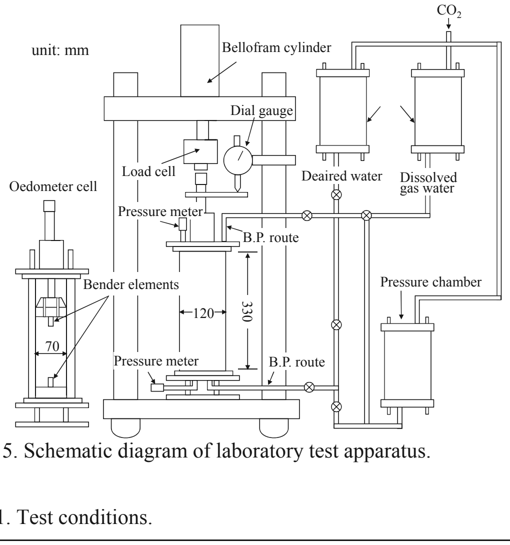

Figure 5. Schematic diagram of laboratory test apparatus.

Table 1. Test conditions.

Test Case	Consolidation stress (C.S.) (kPa)	Back pressure (B.P.) (kPa)	C.S. at B.P. reduction (kPa)
1	100	500	20
2	100	100, 300, 500	100
3	100	100, 300, 500	20

Thereafter, in the Case 2, the back pressure was decreased to atmospheric pressure under a consolidation stress of 100 kPa. On the other hand, in the Case 1 and 3, it was decreased after the consolidation stress was decreased to 20 kPa. Therefore, it would seem that the effects of the sample disturbance in Case 3 are larger than those in Case 2, because the vertical stress of Case 3 at stress release is lower than that of Case 2.

Unconfined compression tests (sample diameter is 50 mm, height is 100 mm, loading rate is 1 mm/min) were performed on the specimens prepared by above procedure.

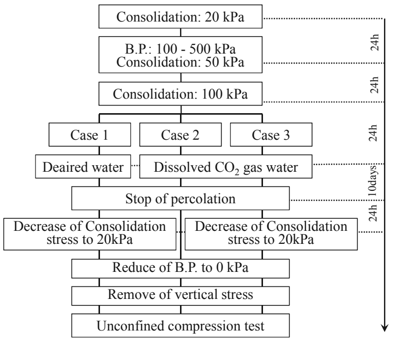

Figure 6. Test process of laboratory test.

4.2 Unconfined compression test results

Figure 7 shows the stress strain relations of unconfined compression tests on all specimens. Figure 8 shows the relations between the unconfined compression strength and the back pressure at consolidation. It is found that the strengths in Case 2 and 3 permeated CO_2 gas dissolved water are lower than those in Case 1 permeated deaired water. It is also found that the strengths in Case 2 and 3 decrease with the increase of back pressure.

Figure 9 shows the relations between the deformation modulus, E_{50}, and the back pressure. Although E_{50} in Case 2 and 3 on back pressure of 100 kPa has some scatter because the degree of CO_2 gas dissolution is low, E_{50} decreases with the increase of back pressure due to the exsolution of dissolved gas in the pore water in the case of the back pressure of 300 and 500 kPa. However, the strengths in Case 3 had not become lower than those in Case 2.

Figure 10 shows the typical time histories of vertical stress, back pressure and axial displacement during the stress release. It is found that the change of axial displacement is not recognized during the decrease of vertical stress and back pressure in all test cases. On the other hand, the axial displacement increases after the release of vertical stress and back pressure in the Case 3. Although the data recording is stopped halfway in the Case 2, the increase of axial displacement was recognized after the release of vertical stress and back pressure. Therefore, it would seem that the difference of strength between the Case 2 and the Case 3 is not recognized, because the sample disturbance was produced after the stress release. It is said that the occurrence of the sample disturbance with the swelling or cracking was delayed by the effect of the cohesion of sample having much clay content. In actuality, when the sampling core was retrieved from the deep lake bottom, the swelling or cracking of core surface is observed after the time of some extent passed. Thus, it is found that the strength of sample becomes low due to the effect of the exsolution of dissolved gas on both on-board and laboratory tests.

Next, the relations between the reduction of strength and the water depth (pressure) are compared. Figure 11 shows the relations between the strength ratio of Case 1 to Case 2, 3 and the water depth converted the solubility of CO_2 gas into that of CH_4 gas. In this figure, unconfined compression test results using the intact samples retrieved from the Lake Baikal (Kataoka et al. 2009) and the triaxial compression test results using intact Liestranda and Bothkennar clays (Lunne et al. 2001) were also plotted.

Test results of Kataoka et al. (2009) are for samples retrieved from the different water depth areas in the Lake Baikal, and the strength ratio is average value of the mud volcano samples (high gas concentration) and the reference samples (low gas concentration) on same area. On the other hand, test results of Luune et al. (2001) are for samples permeated CH_4 gas dissolved water under the different pressure (0 to 15 MPa), as similar to this study method.

It is found from this figure that the strength ratios decrease with the increase of water depth. In other words, it is found that the effects of the sample disturbance become large with the increase of gas concentration (water depth). Although the results of Kataoka et al. have some scatter, the reduction of strength with depth is larger than that in this study. This reason seems that the effects of the sample disturbance in intact samples are larger than those in reconstituted samples. On the other hand, the reduction of strength in the results of Lunne et al. is lower than in this study. It would seem that the effects of the sample disturbance were decreased by the reconsolidation during the triaxial test. From these test results, it would seem that the in-situ strength can be estimated roughly from the disturbed samples retrieved from deep lake bottom by the measuring the concentration of dissolved gas.

5 CONCLUSIONS

The strength of samples retrieved from GH-bearing ground is decreased by the sample disturbance due to the exsolution of dissolved gas during the sampling. The reduction of strength becomes large with the increase of dissolved gas concentration.

From the laboratory tests which simulate the stress relief from bringing the samples to the lake surface, it was recognized that the effects of the sample disturbance become large with the increase of gas concentration. It was also showed that the in-situ strength can be estimated roughly from the disturbed samples.

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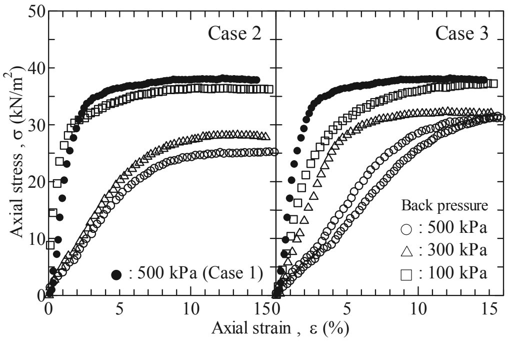

Figure 7. Unconfined compression test results.

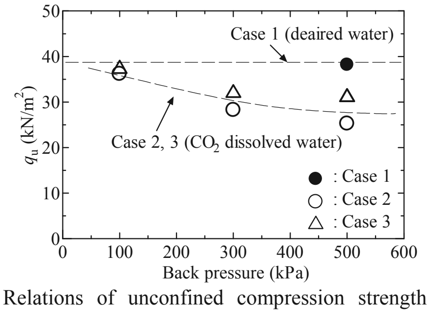

Figure 8. Relations of unconfined compression strength and back pressure.

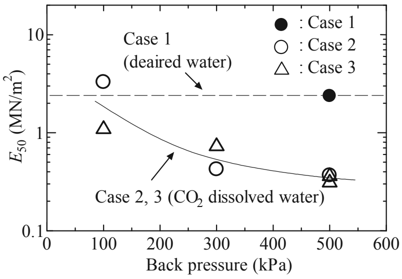

Figure 9. Relations of deformation modulus and back pressure.

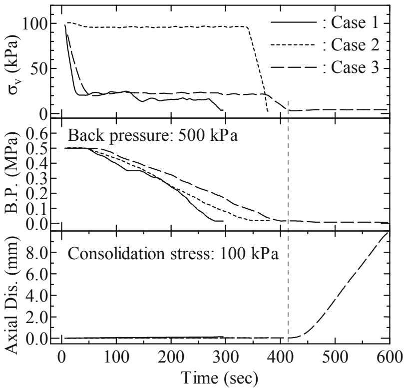

Figure 10. Time histories of vertical stress, back pressure and axial displacement.

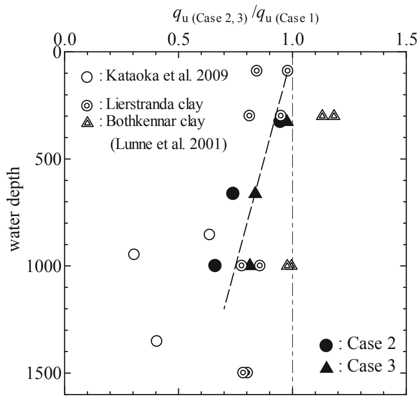

Figure 11. Relations of strength ratio and water depth.

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