Soil properties of the shallow type methane hydrate-bearing sediments in the Lake Baikal

Propriétés du sol du dépôt lacustre contenant de l'hydrate de méthane de type surface au lac Baïkal

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ABSTRACT
The purpose of this study is to understand the soil properties of grounds contained shallow type methane hydrates. For this study, the surveys were conducted in the Lake Baikal, Russia in 2005-2007, existed shallow type methane hydrates, and the several kinds of tests (physical and mechanical tests) were preformed for the lake-bottom sediments. The tested samples were collected from the mud volcano ground contained shallow type methane hydrates and the reference ground at same area. From the results, it was found that the reference samples in the Lake Baikal have no marked differences in the soil properties of the sediment obtained from other sea-bottom areas. On the other hand, the strengths and shear modulus of the mud volcano samples obtained from the on-board tests were lower than those of the reference samples.

RÉSUMÉ
La présente recherche a pour objet d'apporter des éclaircissements sur les propriétés du sol de la terre contenant de l'hydrate de méthane de type surface. Pour cela, des reconnaissances ont été menées de 2005 à 2007 au lac Baïkal, Russie, où il existe ce type d'hydrate de méthane ainsi que divers essais (physiques et mécaniques) du dépôt lacustre. Les échantillons analysés ont été prélevés de la zone de volcan de boue contenant de l'hydrate de méthane de type surface et de la terre de référence de la même zone. Pour les échantillons de référence, les résultats ont montré que les propriétés du sol du dépôt lacustre du Baïkal n'accusaient aucune différence notable avec celles d'autres dépôts sous-marins, alors que pour les échantillons prélevés de la zone de volcan de boue, la résistance et la vitesse d'onde de cisaillement ont été plus faibles que celles des échantillons de référence.

Keywords : Methane hydrates, Site investigation, Unconfined compression test

1 INTRODUCTION

Gas (e.g., methane gas) hydrates are solid, ice-like substances composed of methane gas and water. Natural gas hydrates exist worldwide in marine sediment, in sediments of deep lakes, and in polar sediments associated with permafrost conditions. Geotechnical studies on natural gas hydrates, which is receiving attention as a next-generation energy source, are proceeding. On the other hand, the release of gas during the decomposition of gas hydrates may affect the environment. Moreover, extensive recovery of methane hydrates reduces the stability of the seabed and induces the settlements or underwater landslides.

Methane hydrates existing below sea- and lake-bottom sediments are classified into two types; deep type and shallow type methane hydrates. Efforts to develop methane hydrates around Japan are conducted in the Nankai Trough (e.g., Matsumoto et al. 2004). Methane hydrates of this area belong to "deep type methane hydrates", because they are observed in a zone immediately above a Bottom-simulating reflector (BSR). Methane hydrates are also being studied in the Sea of Okhotsk off Sakhalin Island (e.g., Shoji et al. 2005), the Gulf of Mexico (e.g., Yun et al. 2006), and the Lake Baikal in Russia (e.g., Kuzmin et al. 2000). Methane hydrates of these areas belong to "shallow type methane hydrates", because they are recovered from depths of a few meters below sea- and lake-bottom. Shallow type methane hydrates are cheaper and easier to retrieve than deep type. However, most studies on methane hydrates are applied to deep type in the engineering field (e.g., Clayton et al. 2005). Relatively few studies have focused on the soil properties of sea-bottom ground (e.g., the Gulf of Mexico).

The purpose of this study is to understand the soil properties of grounds contained shallow type methane hydrates. For this study, the surveys were conducted in the Lake Baikal, Russia in 2005-2007, existed shallow type methane hydrates, and lake-bottom sediments were collected to perform the several kinds of tests.

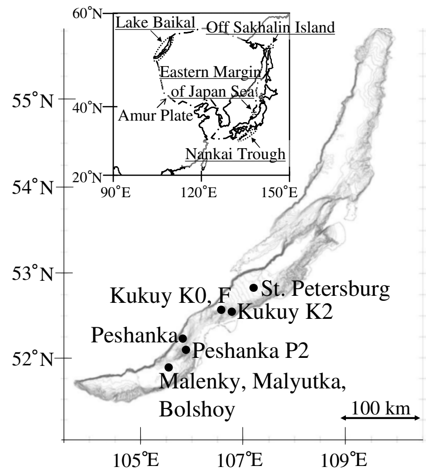

Figure 1. Sampling sites of the Lake Baikal (solid circles show sampling sites).

2 SURVEY AND SOIL SAMPLING

The samplings of lake-bottom sediments were conducted at six sites in the south area of the Lake Baikal through 2005-2007, as shown in Figure 1. It is already reported that methane hydrates in the Lake Baikal are formed at immediately beneath lake-bottom of the mud volcano that are observed the eruption of cool spring water contained gases by the echo sounder (e.g., Matveeva et al. 2003). Thus, at locations of the mud volcanoes, lake-bottom sediments contained methane hydrates were collected by using a gravity core sampler (sampler length is 5 m, diameter is 10 cm and weight is 700 kg). After core samplings, these cores were cut into 1-m interval. Then, each section was longitudinally halved for the various on-board tests. Samples for

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the laboratory tests were taken to minimize potential sources of sample disturbance during transportation and trimming. Samples were also collected from the grounds for which methane hydrates have not been confirmed by acoustic exploration. In this paper, these samples called "reference".

Photo 1 shows methane hydrates collected in these surveys. In these photos, the forms of methane hydrates were massive, grains or veins. These hydrates were also observed to differ in forms in the depth direction in the same core, as shown in Photo 1b. This paper reports the results of the on-board tests for 39 cores, and the laboratory tests for 2 cores. Table 1 shows the details for each sample, such as sampling sites, water depth and core length.

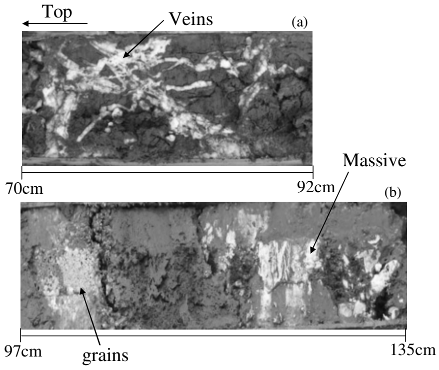

Photo 1. Observation of methane hydrates (Kukuy K2 site).

Table 1. Information on sampling sediments.

Sampling Site	Water Depth (m)	Core Length (m)	On-board tests Mud.	On-board tests Ref.	Lab tests Mud.	Lab tests Ref
1. Kukuy K2	900-1000	1.35-3.30	6	1		
2. Kukuy K0, F	500-510	3.24-4.00	2			
3. St. Petersburg	1420-1430	4.38	1			
4. Peschanka	930-960	4.60	1			
5. Peschanka P2	800-910	2.90-4.60	20	1	1	1
6. Malenky, Malyutka, Bolshoy	1290-1400	1.26-2.80	5	2		

3 TEST METHODS

The on-board tests were conducted for the sediment samples collected from the mud volcano and reference grounds. The on-board tests performed are the compact vane shear test (10-cm intervals; as shown in Photo 2a), cone penetration test (10-cm intervals; Photo 2b) using the compact Yamanaka soil hardness tester (Yamanaka & Matsuo 1962), bender element (BE) test (50-cm intervals; Photos 2c, 2d), and unconfined compression test (50-cm intervals; sample diameter is 35 mm and height is 60 mm; loading rate is 1 mm/min). In the BE test, the one pair of BEs (Photo 2c) was attached to the both side of sediment, as shown in Photo 2d. To check the strength change by transportation, the unconfined compression test was also conducted at the laboratory. The laboratory test samples were collected in the Peschanka P2 site, as shown in Table 1.

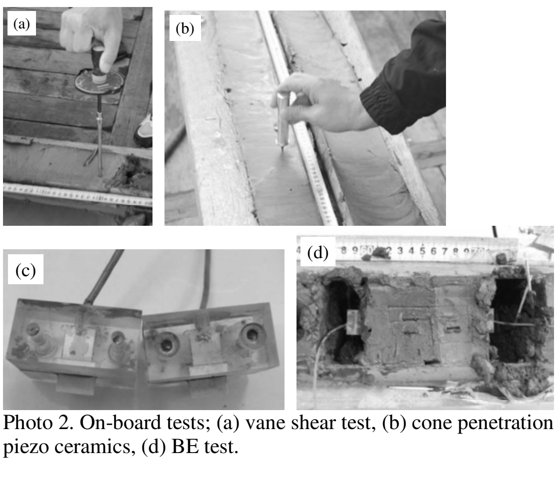

Photo 2. On-board tests; (a) vane shear test, (b) cone penetration test, (c) piezo ceramics, (d) BE test.

The several kinds of physical tests were performed for the samples of the on-board and laboratory unconfined compression tests; soil particle density ρ_s, liquid limit w_L, plastic limit w_p, ignition loss L_i and grain size distribution. Water content w was measured at intervals of 10 cm on the cores.

4 RESULTS AND DISCUSSIONS

4.1 *Results of physical tests*

Figure 2 shows the results of ρ_s, liquidity index I_L (= $(w-w_p)/(w_L-w_p)$), L_i and grain size distribution at different depths. As shown in these figures, ρ_s is from 2.4 to 2.8 g/cm^3, I_L is nearly 1.0 in all samples and L_i is from 3.0 to 8.0 %, regardless of depths. The percentage of the fine fraction exceeds 90% at any depth in the mud volcano and reference areas, and clay accounted from 60 to 80 %. Therefore, it is found that the physical properties of the mud volcano and reference samples are almost similar.

To compare the physical properties obtained from the Lake Baikal sediments and those of other aquatic methane hydrate-bearing sediments, Figure 3 shows the plasticity chart obtained from the Lake Baikal and the Gulf of Mexico sediments (Yun et al. 2006). From this figure, it is known that the sediments from the mud volcano and reference samples of the Lake Baikal have a high liquid state and they differ little from the sediment of the Gulf of Mexico.

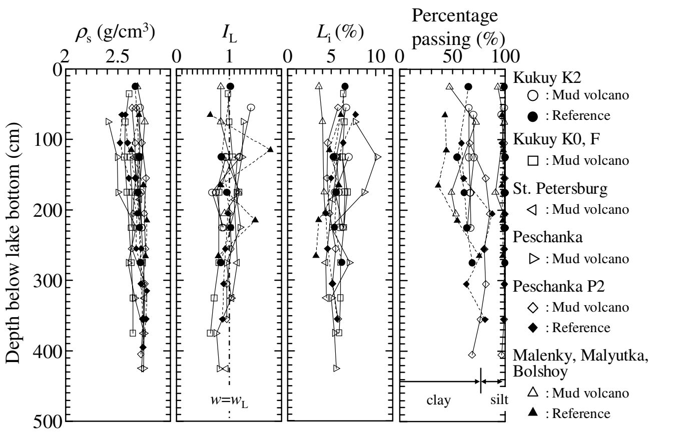

Figure 2. Depth profile of physical properties.

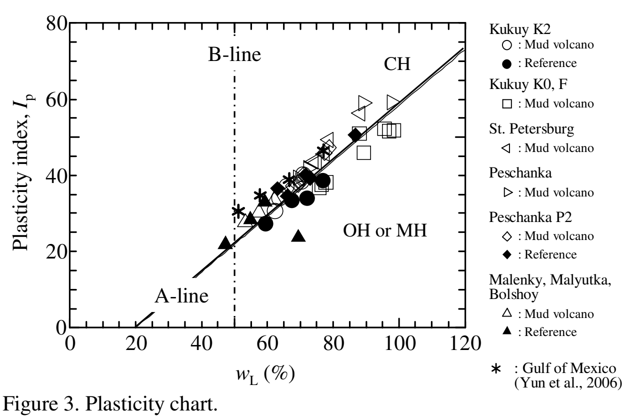

Figure 3. Plasticity chart.

4.2 *Results of mechanical tests*

Figures 4 to 6 show the various on-board tests results (vane shear strength τ_v, cone penetration resistance q_c, and unconfined compression strength q_u) in the Kukuy K2 site (Fig. 4), the Peschanka P2 site (Fig. 5), and the Malenky, Malyutka, Bolshoy site (Fig. 6), together with the profiles of w, with depth. From these figures, it is found that the ws of the deeper strata about 200 cm are almost stable from 60 to 90 %, regardless of the sites. On the other hand, the strengths of the mud volcano samples are lower than those of the reference samples; especially it is shown in q_u.

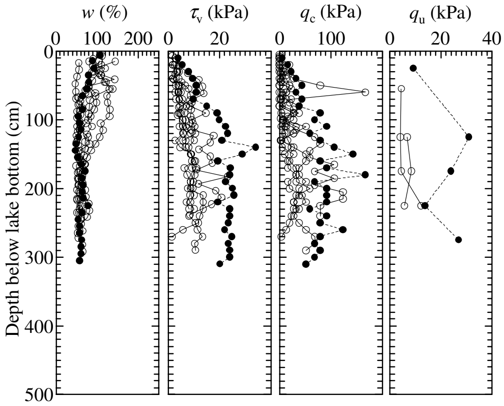

Figure 4. Depth profile of mechanical properties in the Kukuy K2 site. Symbols: filled the reference samples; opened the mud volcano samples.

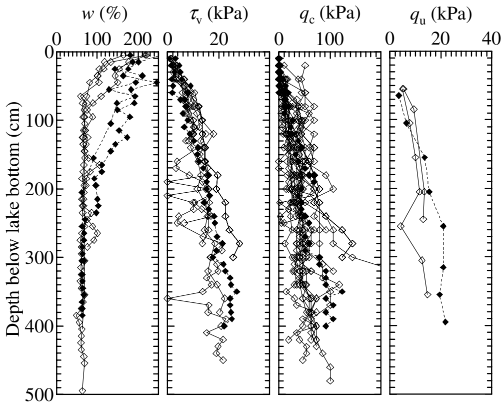

Figure 5. Depth profile of mechanical properties in the Peschanka P2 site. Symbols: filled the reference samples; opened the mud volcano samples.

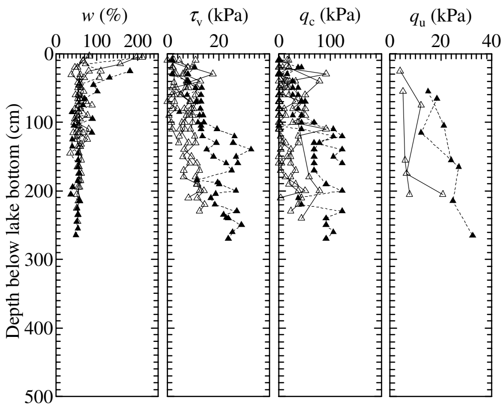

Figure 6. Depth profile of mechanical properties in the Malenky, Malyutka, Bolshoy site. Symbols: filled the reference samples; opened the mud volcano samples.

Figure 7 shows the effective overburden pressure $\sigma'_{v\ in\text{-}situ}$ versus the shear modulus G_{BE} obtained from the on-board BE test. In order to eliminate the effect of the difference in density on the test results, G_{BE} was normalized by dividing it of the void ratio function: $f(e) = (1+e)^{-2.4}$ (Shibuya et al. 1997). From this figure, the fitting line of G_{BE} obtained from the mud volcano samples (solid line) is slightly lower than that of the reference samples (broken line). Therefore, it would seem that the developments of sedimentary structure in the mud volcano sediments are lower than that of the reference sediments.

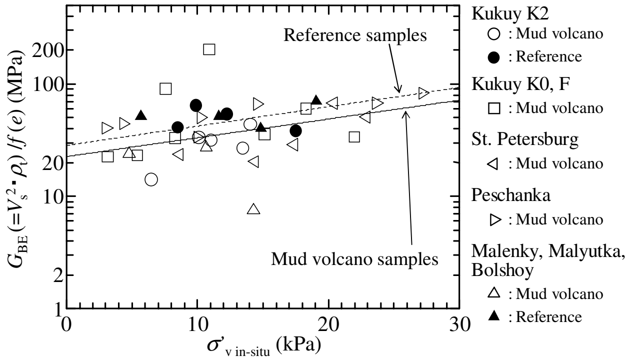

Figure 7. Relationships between $\sigma'_{v\ in\text{-}situ}$ and G_{BE}.

Figures 8 shows the q_u of undisturbed specimens and the q_{ur} of remolding specimens obtained from the Peschanka P2 site. In order to compare the strength change of the sediments samples transportation, the q_u and q_{ur} were shown for the on-board and laboratory tests results. In the reference samples, the values for q_u obtained from the laboratory tests are showed no marked difference from those of the on-board tests. On the other hand, in the mud volcano samples, the q_u of the on-board tests are lower than that of the laboratory tests. The q_{ur} of the remolded sample shows a uniform value of q_{ur}≈5.0 kPa for both the mud volcano and reference samples in the on-board and laboratory tests.

The strength change of the mud volcano samples can be explained as follows: the transported samples were stored vertically for a few days on board for gas venting. The pore water pressure, temporarily rose because of vaporization of dissolved gas in the stress release at sampling, decreased during the time when sample was kept vertical for some time on board and the effective stress increased; as a result, the strength increased.

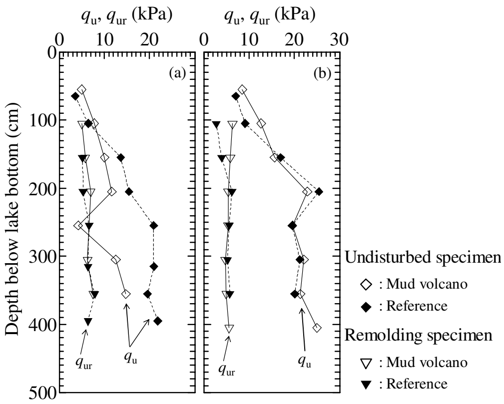

Figure 8. The q_u and q_{ur} profiles measured at the (a) on-board and (b) laboratory tests in the Peschanka P2 site.

4.3 *Soil properties of the mud volcano ground*

As mentioned above, the strengths and shear modulus of the samples collected from the mud volcano grounds were lower than those of the reference grounds, though physical properties of all samples were almost similar. In order to check these reasons, Photo 3 shows the visual observation of the cut surface of the mud volcano sample (Photo 3a) and the reference sample (Photo 3b), respectively. In Photo 3a, the mud volcano sample is observed many voids on the cut surface of the sample. Accordingly, it would seem that the gas content of soil in the mud volcano grounds is likely to be higher than in the reference grounds, because the amount of vaporization of dissolved gas from stress release may be greater in the mud volcano grounds.

In addition, Figures 9 and 10 show the penetration length of the core sampler at the Kukuy K2 site (Fig. 9) and the Peschanka P2 site (Fig. 10). The results of the mud volcano cores are noted only unoccupied methane hydrates to compare with the reference cores. At the Kukuy K2 site, the average of the penetration length of the mud volcano cores is slightly longer than that of the reference cores. Therefore, it is supposed that the lake-bottom condition in the mud volcano grounds are softer than the reference grounds, because the mud volcano grounds are likely disturbed by the emission of water and gas. On the other hand, the penetration length of the Peschanka P2 site shows a high values, averaging 3.82 m for the mud volcano cores and 3.93 m for the reference cores. Therefore, it is considered that the strength of grounds in the Peschanka P2 site is low both in the mud volcano and reference locations. In addition, the low strengths of the mud volcano samples in this site are thought to be attributable mainly to the disturbance of the samples by stress release at sampling.

From these reasons, it is considered that the strengths and shear modulus of the mud volcano samples decreased compared with the reference samples.

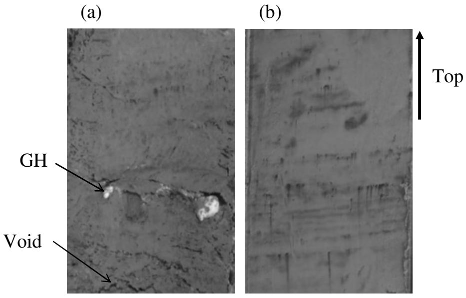

Photo 3. Observations of cut surface of the (a) mud volcano sample and (b) reference sample obtained from the Peschanka P2 site.

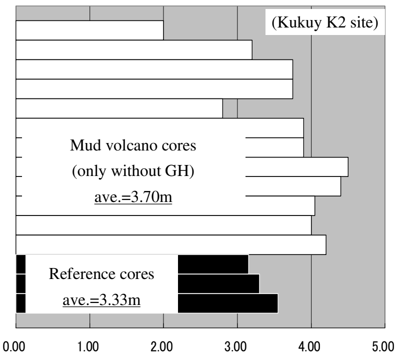

Figure 9. Sampler penetration length at the Kukuy K2 site.

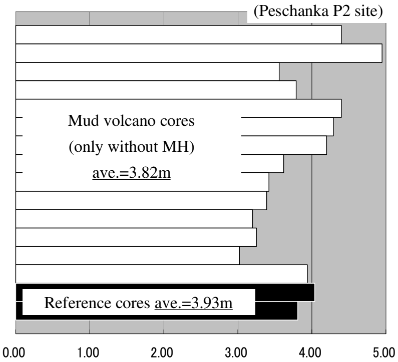

Figure 10. Sampler penetration length at the Peschanka P2 site.

5 CONCLUSIONS

The surveys were conducted in the Lake Baikal, Russia in 2005-2007, and the several kinds of tests were conducted for the lake-bottom sediments. Based on the comparison with the various tests results on the mud volcano and reference samples, the following conclusions were obtained;

1) Cores with methane hydrates were collected from the mud volcano grounds. Methane hydrates observed in the cores appears in massive, grains or veins.

2) Physical properties of the sediments collected from the mud volcano and reference grounds at the same sites were almost similar, regardress of depth.

3) Strengths and shear modulus of the mud volcano samples obtained from the on-board tests were lower than those of the reference samples. It was considered that the sedimentary layers were disturbed by gas and water upwelling from underground and the pressure release during the samples.

4) In the sediments collected from the mud volcano grounds, the strengths obtained from the laboratory test were higher than those of the on-board test.

From these results, it is suggested that when methane hydrates are recovered using methods that involve temperature rise or pressure decrease, which result in dissociation of methane hydrates in shallow type methane hydrate-bearing ground, the sea- or lake-bottom may experience reduction in stability, because of the decreased ground strength.

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