VARIABILITY OF PHYSICAL AND CONSOLIDATION TEST RESULTS FOR RELATIVELY UNIFORM CLAY SAMPLES RETRIEVED FROM OSAKA BAY

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ABSTRACT

Samples collected from both Holocene and Pleistocene layers in Osaka Bay were examined in this study. The objective of this study is to evaluate variations of soil parameters in a sample length of about one meter. The retrieved samples from EL. (elevation) – 37.5 to – 38.5 m and from EL. – 125.5 to – 126.5 m with a length of about one meter were divided into every 25 mm long to trim consolidation specimens. Variations of soil parameters obtained from laboratory tests were evaluated. Clay microfabric was also evaluated by scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP). The clay layers are relatively homogeneous with variation coefficient CV in a range of 0.025 to 0.12 for the consolidation parameters (e , p'_c , C_c and c_v). CV of void ratio e is only 0.025 to 0.056. In contrast, CV values of the other consolidation parameters are significantly greater than this, but the average is less than 0.1. It can be concluded that CV of soil consolidation parameters for the homogeneous natural clay deposits dealt in this study is less than about 0.1. These variations are mainly influenced by sedimentary environment. Even the soil is said to be homogeneous, because the specimen size for the laboratory tests is sufficiently large in consideration of microscopic heterogeneity obtained from SEM and MIP.

Key words: clay, consolidation, soil parameters, variation (IGC: C6/D6)

INTRODUCTION

Osaka Bay clay retrieved from the seabed was investigated for the Kansai International Airport project. The airport located 35 km southwest from the center of Osaka City was constructed on an artificial island that was reclaimed 5 km off the Senshu area in Osaka Bay. The first phase of the Airport with only one runway is in operation since September, 1994, and the second phase is under construction aimed the second runway (will open in 2007) paralleling to the first one. Generally in practice, laboratory tests are conducted for specimens trimmed in an interval of more than one meter depth. Soil parameters obtained from consolidation tests conducted at every two meters depth in Osaka Bay showed a significant variation (Tanaka et al., 2003a). It has not been clarified yet whether the variation was derived from geological heterogeneity; even Tanaka et al. (2003b) discussed test results of a precise cone penetration test applied to greater depths.

In this study, samples collected from both Holocene and Pleistocene layers were examined on their physical and consolidation properties. The objective of this study

is to evaluate variations of soil parameters in a length of about one meter. Variation of clay microfabric observed with scanning electron microscope (SEM) was also statistically analyzed in association with pore entrance distribution obtained by mercury intrusion porosimetry (MIP).

Most of Japanese marine clays are very homogeneous; however, they are not perfectly homogeneous because they deposited in a natural condition. One of the objectives of this study is to evaluate the reliability of a limited number of test results in practice for the marine clay.

Undisturbed samples used in this paper were obtained from the Osaka Bay during the in situ investigation for the second construction phase of the Kansai International Airport. A piston sampler of hydraulic operated type was used for soft and slightly hard clays up to EL. (elevation) – 120 m, and a Denison sampler was used for hard clays deeper than EL. – 120 m. Both sampling methods were carried out by the Port and Airport Research Institute (PARI), formerly known as the Port and Harbour Research Institute (PHRI) wire line system (Horie et al., 1984; Kanda et al., 1991), which was also illustrated in Watabe et al., (2002). The inner diameter and the length

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of sampling tube are 80 and 1000 mm, respectively. At the boring point, the water depth was 19 m, the thickness of Holocene clay layer was 25 m, and the Pleistocene clay layer deposited was more than 350 m thick alternately with some sandy layers. The sampling method and the characteristics of the soils collected from the Osaka Bay were reported in detail by Horie et al. (1984), Ishii et al. (1984), Tsuchida et al. (1984), Kanda et al. (1991), Akai et al. (1995), Akai (2000) and Watabe et al. (2002). According to Watabe and Tsuchida (2001a), the residual effective stress is about one fifth of the effective overburden stress σ'_{v0} and the sample quality is classified as very good. The consolidation settlement was discussed by Nakase (1987) and Duncan (1993), and undrained shear strength was discussed by Watabe et al. (2002).

The Holocene clay deposited within the last 10,000 years. The underlying Pleistocene deposit includes several major sandy soil layers between the clay layers. The clay at EL. -140 m was deposited 270,000 years ago and that at EL. -210 m was deposited 440,000 years ago. Figure 1 shows the soil profile and values of liquid limit (w_L), plastic limit (w_p) and natural water content (w_n); contents of clay ($\leq 5 \mu\text{m}$), silt ($> 5 \mu\text{m}$ and $\leq 75 \mu\text{m}$), sand ($> 75 \mu\text{m}$ and $\leq 2 \text{ mm}$); density of soil particles (ρ_s); void ratio (e); consolidation yield stress (p'_c) obtained by CRS (constant rate of strain) consolidation tests with an axial strain rate of 0.01%/min; and overconsolidation ratio (OCR) defined as p'_c/σ'_{v0} , where σ'_{v0} is calculated by summing the effective unit weight of clay as $\gamma' = 6.9 \text{ kN/m}^3$. The OCR is essentially constant with depth and equals 1.50 (standard deviation SD=0.16), indicating slight overconsolidation, but it is, generally, in normal consolidation from mechanical stress history (Akai et al., 1995; Akai, 2000; Watabe et al., 2002). Tanaka and Locat (1999) indicated that the consolidation behavior is possibly characterized by diatom fossils which are abundantly contained in the Osaka Bay clay. The greater the abundance of diatom fossils, the greater the contraction characterized.

TEST AND OBSERVATION PROGRAM

In this study, samples retrieved from both a Holocene layer at EL. -38 m (G.L. -19 m) and a Pleistocene layer at EL. -126 m (G.L. -107 m) were examined. Two retrieved samples with a length of about one meter and a diameter of 80 mm were divided into every 25 mm of length to trim consolidation specimens with 60 mm in diameter and 20 mm in height. The following parameters obtained from laboratory tests were evaluated: i) natural water content (w_n); ii) Atterberg's limits (liquid limit (w_L) and plastic limit (w_p)); iii) contents of clay, silt and sand; iv) soil particle density (ρ_s); v) soil bulk density (ρ_t); vi) void ratio (e); vii) consolidation yield stress (p'_c); viii) compression index (C_c); and ix) coefficient of consolidation (c_v). Clay microfabric was also evaluated by x) scanning electron microscopy (SEM) and xi) mercury intrusion porosimetry (MIP). The test program corresponding to the each specimen divided from the samples is listed in Table 1.

w_n , w_L , w_p , ρ_s and grain size distribution were first examined before carrying out the series of consolidation tests by using soil chips from specimen trimming. Constant rate of strain consolidation tests (CRS tests) were then carried out for the trimmed clay specimens. ρ_t , e , p'_c , compression index defined as the gradient of the steepest slope in e -log p relationship (C_c), compression index at a consolidation pressure greater than 5000 kPa in e -log p relationship (C_c^*) and c_v defined as a constant value in normal consolidation were obtained from the CRS tests. The CRS tests were conducted with a back pressure of 98.1 kPa and in a strain rate of 0.02%/min.

In addition, the soil chips from specimen trimming were also examined by SEM and MIP. As a fundamental condition of the soil specimen for SEM observation, it is necessary to remove the pore water of clayey soil completely, because the observation chamber of SEM is in vacuum state. Freeze-cut-drying method is believed to be an effective method (Shi et al., 1999; Kang et al., 2003;

Fig. 1. Physical and consolidation profiles of Osaka Bay clay

Table 1. List of tested samples

Elevation E.L. (–m)	Atterberg limits	Grain size	CRS	SEM	MIP	Elevation E.L. (–m)	Atterberg limits	Grain size	CRS	SEM	MIP
37.500–37.525	○	○	○		○	125.500–125.525	○	○			○
37.525–37.550		○	○	○	○	125.525–125.550				○	○
37.550–37.575		○	○		○	125.550–125.575					○
37.575–37.600		○	○		○	125.575–125.600			○		○
37.600–37.625	○		○		○	125.600–125.625	○	○	○		○
37.625–37.650		○	○	○	○	125.625–125.650				○	○
37.650–37.675		○	○		○	125.650–125.675			○		○
37.675–37.700		○	○		○	125.675–125.700			○		○
37.700–37.725	○	○	○		○	125.700–125.725	○	○			
37.725–37.750		○	○		○	125.725–125.750			○		○
37.750–37.775		○	○		○	125.750–125.775				○	○
37.775–37.800		○	○	○	○	125.775–125.800			○		○
37.800–37.825	○	○	○			125.800–125.825	○	○	○	○	○
37.825–37.850		○	○		○	125.825–125.850			○		○
37.850–37.875		○	○	○	○	125.850–125.875			○		○
37.875–37.900		○	○		○	125.875–125.900			○		○
37.900–37.925	○	○	○		○	125.900–125.925	○	○	○		○
37.925–37.950		○	○		○	125.925–125.950			○	○	○
37.950–37.975		○	○	○	○	125.950–125.975			○		○
37.975–38.000		○	○		○	125.975–126.000			○		○
38.000–38.025	○	○	○	○	○	126.000–126.025	○	○	○	○	○
38.025–38.050		○	○		○	126.025–126.050					
38.050–38.075		○	○		○	126.050–126.075			○		○
38.075–38.100		○	○		○	126.075–126.100			○		○
38.100–38.125	○	○	○	○	○	126.100–126.125	○	○	○		○
38.125–38.150		○	○		○	126.125–126.150			○		○
38.150–38.175		○	○		○	126.150–126.175			○	○	○
38.175–38.200		○	○	○	○	126.175–126.200			○		○
38.200–38.225	○	○	○	○	○	126.200–126.225	○	○	○		○
38.225–38.250		○	○	○	○	126.225–126.250			○		○
38.250–38.275		○	○		○	126.250–126.275			○	○	○
38.275–38.300		○	○		○	126.275–126.300			○		○
38.300–38.325						126.300–126.325	○				
38.325–38.350						126.325–126.350					
38.350–38.375						126.350–126.375					
38.375–38.400						126.375–126.400					
38.400–38.425						126.400–126.425	○				
38.425–38.450						126.425–126.450					
38.450–38.475						126.450–126.475					
38.475–38.500						126.475–126.500					

Watabe et al., 2004). This method was adopted in this study both to minimize the sample disturbance caused by either shrinkage or expansion of porous wet media and to obtain a flat observation surface. In freeze drying, a soil sample trimmed to an appropriate size and shape is immersed into liquid nitrogen (-196°C) for instant freezing to avoid formation of crystallized ice in pores. The crystallized ice consequently leads to volumetric expansion of the soil. Then, the frozen specimen is transferred to the vacuumed chamber of a freeze dryer for sublimation at least for 24 hours. The sample size is about 3 mm in thickness and 30 to 40 mm in length of stick shape. For SEM observation, to determine the observation surface of specimen, fracturing was conducted at freeze condition. This corresponds to the freeze-cut-drying method in which a frozen sample is cut by tensional fracturing (Shi et al., 1999). Tensional fracturing is done by holding one end of the sample and impacting a strike with a swinging hammer causing a tensional cut in the middle part of the sample. This is to avoid any disturbance accompanied by either knife cutting or shearing. It is noted that tensional cut is necessary only for SEM, but not for MIP.

In the SEM observation, four edges of a square with a side of 0.3 mm in each specimen were photographed by four different magnifications at 5000, 2500, 1000 and 500 times. The SEM photographs were image-analyzed by transforming the photographed image in gray scale from 0 to 255 into a binarized black and white image with a certain threshold value. In this study, the threshold value was set in 200. The black percentage in the binarized black and white image was calculated.

The specimen height for the consolidation test is 20 mm, while the width of SEM image in a magnification of 500 times is about 0.3 mm. The scale continuity in this discussion is retained, because the scale gap between two approaches from laboratory tests and microscopy are only 70 times. MIP can quantitatively evaluate the pore size distribution which is an important component of the fabric observed in SEM images.

TEST RESULTS AND DISCUSSIONS

Variation of Physical Properties

Physical properties (w_n , w_p , w_L , particle size fractions, ρ_s and e) of the Holocene and the Pleistocene clays are shown in Figs. 2 and 3, respectively. Frequencies, mean value (MV) and standard deviation (SD) of these parameters are also shown in the figures. Both clays have essentially common properties as $w_L=80\%$, $w_p=30\%$, plasticity index (I_p) of 50, clay fraction of 30 to 40%, sand fraction of less than 20%. The w_n of the Holocene clay ($73.09 \pm 2.06\%$) is slightly less than w_L (i.e. liquidity index I_L of about 0.86 is slightly smaller than unity), and w_n of the Pleistocene clay ($41.76 \pm 2.19\%$) is slightly larger than w_p (i.e. liquidity index I_L of 0.24 is slightly larger than zero). SD of w_n for the both clays is only about 2%. Corresponding to this, the profile of ρ_t of the Holocene clay ($1.550 \pm 0.010 \text{ Mg/m}^3$) is very homogeneous. In contrast, that of the Pleistocene clay ($\rho_t = 1.726 \pm 0.030 \text{ Mg/m}^3$) shows significant variation caused by a higher ρ_t value close to 1.8 Mg/m^3 at around EL. -126.05 m . In fact, w_n also shows a slight smaller value at this depth.

Fig. 2. Profiles of physical properties with depth in the Holocene clay

Fig. 3. Profiles of physical properties with depth in the Pleistocene clay

Comparing between SD/MV (= CV: variation coefficient) values for w_n and ρ_t (0.028 and 0.006 respectively for the Holocene clay and 0.052 and 0.017 respectively for the Pleistocene clay), it can be said that w_n is more sensitive than ρ_t .

The profile of ρ_s of the Holocene clay ($= 2.644 \pm 0.028 \text{ Mg/m}^3$) is slight variable with CV of 0.011, corresponding to the profile of e (1.954 ± 0.058 with CV of 0.030). The ρ_s shows high values of 2.69 to 2.70 Mg/m^3 at around EL. -37.75 m and -38.15 m resulting higher e values at these depths. This fact means that, if MV of 2.644 Mg/m^3 was adopted as ρ_s to calculate e for all depths, e would show a very homogeneous profile. It cannot be judged which one is appropriate between the profiled ρ_s or the constant ρ_s . On the other hand, the profile of ρ_s of the Pleistocene clay ($= 2.695 \pm 0.013 \text{ Mg/m}^3$) is very homogeneous with CV of 0.005. Because the profiled ρ_s and the constant ρ_s are essentially the same for the Pleistocene clay, the profile of e just corresponds to the profile of ρ_t . The large value of ρ_t at EL. -126.05 m indicates silty deposit; however, this cannot be clearly confirmed from grain size fractions and SEM images (see Fig. 11).

Variation of Consolidation Properties

Relationships between void ratio and consolidation stress (e - $\log p'$) for (a) the Holocene clay and (b) the Pleistocene clay are shown in Fig. 4. All curves for the Holocene and the Pleistocene clays respectively converge on each respective curve under high p' range, though ini-

Fig. 4. Relationships between void ratio and consolidation pressure

Fig. 5. Profiles of consolidation properties with depth in the Holocene clay

tial e values show some variation. The inversed S-shaped curves with clear yielding, even in the Holocene clay, are characteristically observed for aged natural clays. The curve without a clear yielding point in Fig. 4(a) corresponds to EL. -37.59 m, and the three curves from smaller e values in Fig. 4(b) correspond to around EL. -126.05 m. From Fig. 3 which shows slightly smaller w_L , slightly larger sand fraction, larger ρ_i and smaller e at EL. -126.05 m than those at other depths, the latter is judged to be derived from geological heterogeneity.

Profiles of consolidation parameters (p'_c , C_c , C_c^* and c_v) with depth for the Holocene and the Pleistocene clays are shown in Figs. 5 and 6, respectively. In the Holocene clay, p'_c ($=133 \pm 10$ kPa) slightly increases with depth. SD of C_c is 0.158, but SD of C_c^* is only 0.063. Variation coefficient (CV), however, is the same as 0.10 for both C_c and C_c^* . In addition, the specimen from EL. -37.59 m, corresponding to a smaller p'_c (101 kPa) and a smaller C_c (1.043) which are possibly caused by sample disturbance, is not identified in the profile of C_c^* which represents compressibility in normal consolidation range.

In the Pleistocene clay, p'_c is evaluated as 1028 ± 79 kPa, but it shows a larger p'_c (1237 kPa) at around EL. -126.05 m. This larger p'_c is caused from the unclear yielding shoulder of e -log p curves as shown in Fig. 4(b). $C_c = 0.921 \pm 0.108$ and $C_c^* = 0.569 \pm 0.048$ are about 40%

and about 5% smaller than those for the Holocene clay, respectively. The latter (small difference between the clays) indicates that both the Holocene clay and the Pleistocene clay are essentially the same consolidation properties in normal consolidation range. This fact is strongly supported by the same w_L values for the both clays (see Fig. 2). C_c/C_c^* is calculated as 1.6, which is smaller than that of 2.5 calculated for the Holocene clay.

In order to evaluate the variation of e , p'_c , C_c and c_v , these parameters are normalized by their mean values MV, respectively, and profiles of the normalized parameters of the Holocene clay and the Pleistocene clay with depth are shown in Fig. 7 and 8, respectively.

In the Holocene clay, standard deviation SD values of normalized e , p'_c , C_c and c_v , i.e. variation coefficient CV values of e , p'_c , C_c and c_v , are 0.024, 0.075, 0.104 and 0.072, respectively. CV of e (0.024) is the smallest and that of C_c (0.104) is the largest among them. In the Pleistocene clay, CV of e (0.056) is about twice of that in the Holocene clay, which probably caused from the smaller e values at around EL. -126.05 m. CV of p'_c (0.077) is almost the same as that in the Holocene clay. CV of C_c (0.117) is also the same level as that in the Holocene clay. However, CV of c_v (0.109) is about 50% larger than that in the Holocene clay.

Examining the clay samples retrieved from both the

Fig. 6. Profiles of consolidation properties with depth in the Pleistocene clay

Fig. 7. Profiles of normalized consolidation parameters with depth in the Holocene clay

Fig. 8. Profiles of normalized consolidation parameters with depth in the Pleistocene clay

Holocene layer and the Pleistocene layer in Osaka Bay and divided into every 25 mm of length, it is resulted that the clay layers are relatively homogeneous with CV of the consolidation parameters (e , p'_c , C_c and c_v) in a range of 0.025 to 0.120. CV of e is only 0.025 in the Holocene clay and 0.056 in the Pleistocene clay, but CV of the other consolidation parameters (p'_c , C_c and c_v) obtained from CRS tests are greater than these values, but the average is less than 0.1. This value is consistent with the CV of undrained shear strength profile of Osaka Bay clay (CV = 0.075) indicated in Watabe and Tsuchida (2001b), in which the strength was obtained by the recompression triaxial compression and extension tests proposed by Berre and Bjerrum (1973). Therefore, it can be concluded that CV values of soil consolidation parameters obtained from CRS tests for the homogeneous natural clay deposits examined in this study are less than about 0.1.

MV and CV of 697 kPa and 0.17, respectively, for p_c had been obtained from a series of incremental loading oedometer tests separately carried out for the Pleistocene clay (10 results for about 20 m thick layer). In a case of slight overconsolidation, the representative p_c for the thick layer does not exist, because it increases with depth. Thus, if MV is assumed to represent p_c for the whole layer without regarding the depth profile, CV results a large value. In practice, sampling and laboratory tests are carried out with interval of 1 to 3 m deep. The middle depth of 0.8 to 1.0 m long sample represents the depth of the whole sample. The detailed depth of each sample trimmed is not concerned. From the above results obtained in this study, CVs of both physical and consolidation test results are smaller than 0.1, indicating that it is reasonable to represent as one depth for each sample with about 1 m long.

Because consolidation parameters are examined every one or a few meter(s) in an ordinary ground survey for

practical design, it is difficult to statistically evaluate the variation of obtained parameters if the soil layer is not perfectly homogeneous. Thus, it cannot be judged if the tested specimen was representative of the examining layer or not. Accordingly, it is important to select a representative specimen in the layer in association with the profiles of physical and consolidation properties.

Heterogeneity of Microfabric

Observed SEM images and those binarized images for the Holocene clay at EL. -37.96 and -38.19 m and the Pleistocene clay at EL. -126.01 and -125.54 m are shown in Figs. 9, 10, 11 and 12, respectively. In Figs. 9 and 11, the images in magnification of both 5000 and 2500 times show enlarged structure of soil microfabric. On the other hand, in Figs. 10 and 12, the images in magnification of both 5000 and 2500 times show particular parts contained in the soil microfabric such as pyrite (Fig. 10) and diatom (Fig. 12).

Profiles with depth (a , b , c and d) and frequencies (e , f , g and h) on black percentage in the binarized black and white images for the Holocene clay and the Pleistocene clay are shown in Figs. 13 and 14, respectively. Here, the black percentage indicates a percentage of pores in the section. Width shown by broken line shows a range of $MV \pm SD$. SD value tends to decrease when the magnification decreases as follows: from 9.0% at 5000 times down to 4.3% at 500 times for the Holocene clay and from 12.2% at 5000 times down to 5.7% at 500 times for the Pleistocene clay.

In the Holocene clay (Fig. 13), SD decreases when the magnification decreases in order of 5000, 2500 and 1000 times, indicating that the impression of the SEM images varies with these magnifications. However, SD values at both magnifications of 1000 and 500 times are in the same level as 4.3%. This fact can be visually impressive in Fig.

Fig. 9. SEM and binarized images of the Holocene clay at EL. -37.96 m

9.

In the Pleistocene clay (Fig. 14), SD tends to decrease when the magnification decreases. SD at magnification of 2500 times (6.3%) is about half of that at magnification

of 5000 times (12.2%), but SD values at 2500, 1000, and 500 times are in the same level as around 6%. This fact can be visually impressive in Fig. 11.

In the Holocene clay, SD values at magnification of

Fig. 10. SEM and binarized images of the Holocene clay at EL. -38.19 m

2500 times and at magnification of both 1000 and 500 times are 72% and 48%, respectively, of SD value at magnification of 5000 times. This fact indicates that every SEM image with a high magnification of 5000, 2500 and

1000 times gives different impression, but that every SEM image with a low magnification of 1000 and 500 times gives a similar impression. In the Pleistocene clay, SD value at magnification of 2500 times is 52% of that at

Fig. 11. SEM and binarized images of the Pleistocene clay at EL. -126.01 m

magnification of 5000 times, and SD value of 2500, 1000 and 500 times is in the same level. This fact indicates that every SEM image with a high magnification of 5000 and 2500 times gives different impression, but that every SEM

image with a low magnification of 2500, 1000 and 500 times gives a similar impression.

Figure 15 shows relationships (a) MV of black percentage and (b) CV of black percentage versus the magnifica-

Fig. 12. SEM and binarized images of the Pleistocene clay at EL. -125.54 m

tion. Because CV of the black percentage is reflected by the flocculent structure or diatoms, if we observe the specimen in a magnification smaller than the lower limit of magnification corresponding to a constant CV, we can

obtain an image which gives us always the same impression. In Fig. 15(a), MV slightly decreases when the magnification increases, but essentially constant. From CV in Fig. 15(b), it can be said that the variation of the SEM im-

Fig. 13. Profiles of black percentage with depth and frequencies of the binarized images in the Holocene clay

ages becomes significant when observation magnification is greater than 1000 times for the Holocene clay or 2500 times for the Pleistocene clay. Therefore, a representative structure in the microfabric can be observed in an area of $125\ \mu\text{m} \times 100\ \mu\text{m}$ with magnification of 1000 times for the

Holocene clay or $50\ \mu\text{m} \times 40\ \mu\text{m}$ with magnification of 2500 times for the Pleistocene clay, respectively. Here, it is of concern that the analyzed results is strongly affected by the threshold value; however, we confirmed that MV and CV of black percentage increase about 10% and

Fig. 14. Profiles of black percentage with depth and frequencies of the binarized images in the Pleistocene clay

remain constant, respectively, if the threshold value decreased from 200 to 190.

Profiles of the most probable pore entrance diameter D , which correspond to the peak of $\Delta V_p / \Delta \log D_p$, for (a)

the Holocene clay and (b) the Pleistocene clay are shown in Fig. 16. Here, V_p is cumulative pore volume; and D_p is pore entrance diameter obtained from MIP. Width shown by broken line shows a range of $MV \pm SD$, which

is $0.79 \pm 0.18 \mu\text{m}$ for the Holocene clay and $0.28 \pm 0.05 \mu\text{m}$ for the Pleistocene clay. Because grain size distributions for the Holocene clay and the Pleistocene clay are similar to each other from the grain size fractions as shown in Figs. 2(b) and 3(b), the SEM image impression discussed above is not governed by grain size distribution

but it may be governed by pore entrance size distribution. A representative SEM image can be obtained in a scale size (e.g. square root of $125 \mu\text{m} \times 100 \mu\text{m}$ for the Holocene clay and that of $50 \mu\text{m} \times 40 \mu\text{m}$ for the Pleistocene clay) corresponding to 150 times of a representative pore entrance diameter ($0.79 \mu\text{m}$ for the Holocene clay and $0.28 \mu\text{m}$ for the Pleistocene clay) or larger. This is probably a key relationship correlating the microfabric with pore structure.

Because the specimen size for laboratory tests is sufficiently large compared to the scale of microscopic heterogeneity discussed with both SEM images and pore entrance size distributions, the variations of physical and consolidation properties are mainly influenced by sedimentary environment, and even the soil is said to be homogeneous.

CONCLUSIONS

In this study, two clay samples with a length of about one meter retrieved from both the Holocene layer and the Pleistocene layer in Osaka Bay by using thin walled tube sampler with 80 mm in diameter and about one meter in length were divided into every 25 mm of length to trim consolidation specimens with 60 mm in diameter and 20 mm in height. The objective of this study was to exam the variation of physical and consolidation properties for natural clay deposit in Osaka Bay. Variation of consolidation parameters were examined by using the trimmed specimen. Also, variations of physical properties and microfabric were examined by using soil chips from specimen trimming. The followings are derived as conclusions:

- 1) The clay layers are very homogeneous with CV values of physical properties (w_n, ρ_t, ρ_s and e) in a range of

Fig. 15. Relationships of (a) MV of black percentage and (b) CV of black percentage versus the observation magnification

Fig. 16. Profiles of the most probable pore entrance diameter for (a) Holocene clay and (b) Pleistocene clay

0.005 to 0.056. CV of ρ_t and ρ_s is around 0.01 for both the Holocene clay and the Pleistocene clay. CV values of w_n and e are around 0.03 for the Holocene clay and around 0.05 for the Pleistocene clay.

- 2) The clay layers are relatively homogeneous with CV values of consolidation parameters (e , p'_c , C_c and c_v) in a range of 0.025 to 0.120. CV of e is only 0.025 in the Holocene clay and 0.056 in the Pleistocene clay. CV values of consolidation parameters (p'_c , C_c and c_v) obtained from CRS tests are significantly greater than this, but the average is less than 0.1. It can be concluded that CV values of soil consolidation parameters obtained from CRS tests for the homogeneous natural clay deposits examined in this study are less than about 0.1.
- 3) From the test results obtained in this study, CVs of both physical and consolidation test results are smaller than 0.1, indicating that it is reasonable to represent as one depth for each sample with about 1 m long.
- 4) It can be said that the variation of SEM images becomes significant when observation magnification is greater than 1000 and 2500 times for the Holocene clay and the Pleistocene clay, respectively. This means that a representative soil microfabric can be observed in an area of $125\ \mu\text{m} \times 100\ \mu\text{m}$ with a magnification of 1000 times for the Holocene clay and $50\ \mu\text{m} \times 40\ \mu\text{m}$ with a magnification of 2500 times for the Pleistocene clay.
- 5) A representative SEM image can be obtained in a scale size greater than about 150 times of a representative pore entrance diameter. This is a key relationship correlating the microfabric with pore structure.
- 6) Because specimen sizes for laboratory tests is sufficiently large compared to the scale of microscopic heterogeneity discussed with SEM images and pore entrance size distributions, the variations of physical and consolidation properties are mainly influenced by sedimentary environment, even the soil is said to be homogeneous.

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