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1D deformation induced permeability and microstructural anisotropy of Ariake clays

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Abstract. The permeability behavior of Ariake clays has been investigated by constant rate of strain (CRS) consolidation tests with vertical or radial drainage. Three types of Ariake clays, namely undisturbed Ariake clay samples from the Saga plain, Japan (aged Ariake clay), clay deposit in shallow seabed of the Ariake Sea (young Ariake clay) and reconstituted Ariake clay samples using the soil sampled from the Saga plain, were tested. The test results indicate that the deduced permeability in the horizontal direction (k_h) is generally larger than that in the vertical direction (k_v). Under odometer condition, the permeability ratio (k_h/k_v) increases with the vertical strain. It is also found that the development of the permeability anisotropy is influenced by the inter-particle bonds and clay content of the sample. The aged Ariake clay has stronger initial inter-particle bonds than the young and reconstituted Ariake clays, resulting in slower increase of k_h/k_v with the vertical strain. The young Ariake clay has higher clay content than the reconstituted Ariake clay, resulting in higher values of k_h/k_v. The microstructure of the samples before and after the consolidation test has been examined qualitatively by scanning electron microscopy (SEM) image and semi-quantitatively by mercury intrusion porosimetry (MIP) tests. The SEM images indicate that there are more cut edges of platy clay particles on a vertical plane (with respect to the deposition direction) and there are more faces of platy clay particles on a horizontal plane. This tendency increases with the increase of one-dimensional (1D) deformation. MIP test results show that using a sample with a larger vertical surface area has a larger cumulative intruded pore volume, i.e., mercury can be intruded into the sample more easily from the horizontal direction (vertical plane) under the same pressure. Therefore, the permeability anisotropy of Ariake clays is the result of the anisotropic microstructure of the clay samples.

Keywords: CRS test; inter-particle bonds; microstructure; MIP test; permeability anisotropy; SEM test

1. Introduction

Clay particles are generally platy shaped (Mitchell and Soga 2005), and the orientation of the particles and the microstructure formed can influence its consolidation as well as mechanical properties (Delage and Lefebvre 1984, Clennell *et al*. 1999, Sivakumar *et al*. 2002, Hattab *et al*. 2013). For most natural clayey soils, predominant horizontal orientation of platy clay particles can

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lead to permeability anisotropy of soft clay deposits, in which the permeability in the horizontal direction (k_h) is larger than that in the vertical direction (k_v) (Al-Tabbaa and Wood 1987, Leroueil *et al*. 1990, Little *et al*. 1992, Terzaghi *et al*. 1996, Chai *et al*. 2012).

Microstructure of clayey soils can be altered by deformation of a soil mass (Lambe and Whitman 1969). Under one-dimensional (1D) deformation condition, compression in vertical direction can enhance the tendency of horizontal orientation of clay particles and thus increase the degree of permeability anisotropy, which can be termed as strain-induced anisotropy. This phenomenon has been observed by microstructure investigations using scanning electron microscopy (SEM) images (Djéran-Maigre *et al*. 1998, Hicher *et al*. 2000, Cetin 2004, Hattab *et al*. 2010, Hattab and Fleureau 2010, 2011).

Conceptually, the re-orientation of clayey soil particles is influenced by initial alignment of soil particles and inter-particle bonds. Before the inter-particle bonds are broken, the rotation of the soil particles will be limited (Hattab *et al*. 2013). However, the effect of initial inter-particle bonds and clay content on the strain-induced permeability anisotropy behavior is not well investigated and not understood quantitatively. While understanding of permeability anisotropy and its change during deformation process is important for design any geotechnical project on a clayey deposit, especially for preloading a soft clayey deposit with installation of prefabricated vertical drains (PVDs).

In this study, the values of permeability in the vertical direction (k_v) and in the horizontal (k_h) of three different Ariake clay samples were investigated by constant rate of strain (CRS) consolidation tests under both vertical and radial drainage conditions. The particle orientation of the Ariake clay samples before and after the consolidation test was then investigated using SEM images. For the reconstituted Ariake clay samples, the pore size distribution was examined by mercury intrusion porosimetry (MIP) tests. Finally, the link between the microstructural anisotropy and permeability anisotropy, and the effect of inter-particle bonds and clay content on the permeability anisotropy of Ariake clays induced by 1D deformation are discussed.

2. Experimental investigations on permeability anisotropy

2.1 Soil samples

Three types of soil samples were used. One is undisturbed Ariake clay sampled from the Saga plain, Japan, the second type is undisturbed sample from shallow seabed (within 1.0 m depth) from the Isahaya Bay, Ariake Sea, Japan, and the third one is reconstituted Ariake clay. The thin-wall tubes with an inner diameter of 75 mm and a height of 1 m were used to obtain the undisturbed samples. The reconstituted Ariake clay samples were made from the Ariake clay slurry with a water content (w_n) of about 1.5 times of its liquid limit (w_L) and consolidated under a vertical stress of 10 kPa, 20 kPa, 50 kPa and 100 kPa, respectively, before CRS consolidation tests.

Geologically, it has been estimated that in the Saga plain, the Ariake clay was deposited in past 10,000 years (Ariake Bay Research Group 1965). For the shallow seabed clay, its exact age is not investigated, but comparing with the Ariake clay deposited in the Saga plain, it must be much younger. Relatively, the undisturbed Ariake clay sample from the Saga plain is designated as the aged Ariake clay and the undisturbed sample from the shallow seabed of the Ariake Sea as the young Ariake clay. Therefore, in term of inter-particle bonds, from strong to weak, the order of the three types of samples is: the aged Ariake clay, the young Ariake clay and the reconstituted Ariake

Table 1 Physical properties of the soils

Sample	Sedimentary age	Depth (m)	w_n (%)	w_L (%)	w_P (%)	I_P (%)	Clay content (%)
A-1	Aged (Ariake clay in Saga plain)	3.0-3.8	122.3	120.3	56.0	64.3	-
A-2		7.0-7.4	103.8	106.1	53.7	52.4	-
A-3		9.0-9.4	91.5	83.6	50.5	33.1	-
A-4		13.0-13.8	113.5	107.6	59.8	47.8	-
Y-1	Young (clay in shallow seabed of Ariake Sea)	0-0.8	175.0	150.2	44.0	106.2	67.5
Y-2		0-0.8	160.5	143.9	44.2	99.7	62.8
Y-3		0-0.8	165.2	145.6	44.9	100.7	62.3
R-1	Reconstituted (10 kPa)	-	98.7	122.0	84.5	37.5	34.6
R-2	Reconstituted (20 kPa)	-	98.2				
R-3	Reconstituted (50 kPa)	-	90.5				
R-4	Reconstituted (100 kPa)	-	85.7				

clay samples. The physical properties of the soils are summarized in Table 1.

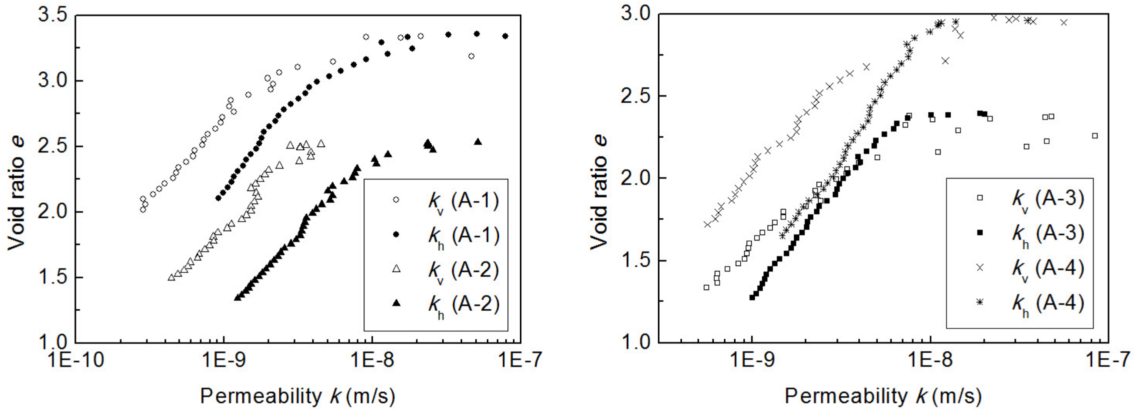
In general, natural water contents (w_n) of the undisturbed samples were slightly higher than their corresponding liquid limits (w_L). The clay contents and water contents of the young Ariake clay samples are higher than those of the reconstituted Ariake clay samples. The dominant clay mineral of the Ariake clay is smectite (Ohtsubo *et al.* 1995). For the samples tested in this study, the clay content (< 5 μm) is in the range of 30-70%.

2.2 Test methods

A CRS consolidometer that can conduct CRS tests with either vertical or radial drainage (Chai *et al.* 2012, Jia *et al.* 2010, 2013) was used to investigate the vertical and horizontal permeabilities of the samples. The CRS tests were carried out according to ASTM D4186-06 (ASTM 2006). For CRS tests with vertical drainage, soil specimens with a diameter of 60 mm and a nominal height of 20 mm were used. The excess pore pressure at the bottom of the specimen was measured during the tests. For CRS tests with radial drainage, annular soil specimens with an outer diameter of 60 mm, inner diameter of 8 mm and a nominal height of 20 mm were used. A cylindrical tube porous stone with an outer diameter of 8 mm and wall thickness of about 3 mm was inserted in the middle of the specimen to provide drainage during the consolidation. The excess pore water pressure at the middle height of the outside perimeter of the specimen was measured during the tests. For all tests, the samples were loaded with a strain rate of 0.02%/min up to about 30% vertical strain, while the consolidation stress was varied and related to the stiffness of the sample. In CRS tests with vertical drainage, the maximum consolidation stresses for the aged Ariake clay and the reconstituted Ariake clay were about 300 to 800 kPa, and for the young Ariake clay were about 50 to 80 kPa.

2.3 Permeability anisotropy

2.3.1 Equations for calculating k_v and k_h



(a) (b)

Fig. 1 Variation of permeability with void ratio (aged Ariake clay)

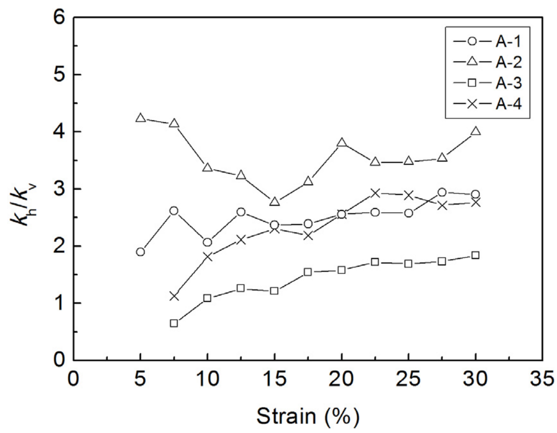


Fig. 2 Variation of permeability ratio with strain (aged Ariake clay)

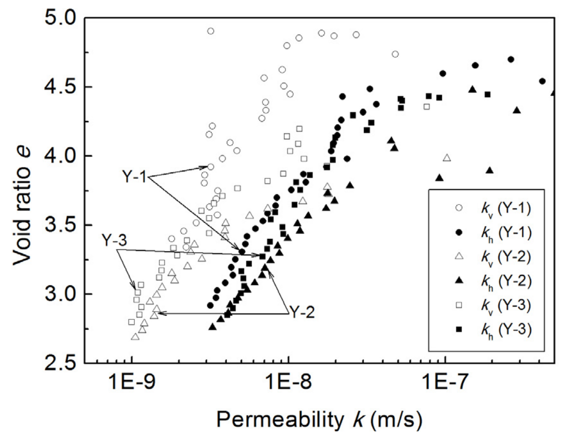


Fig. 3 Variation of permeability with void ratio (young Ariake clay)

For the CRS tests with the vertical drainage, the value of permeability in the vertical direction (k_v) is calculated as

$$k_v = \frac{\gamma_w \cdot \Delta H \cdot \overline{H}}{2 \cdot \overline{u}_b \cdot \Delta t} \tag{1}$$

where γ_w = the unit weight of water; ΔH = the change of the thickness of the specimen; and $\overline{H}$ = the average thickness of the specimen, and $\overline{u}_b$ = the average excess pore water pressure at the bottom of the specimen between t and $t + \Delta t$.

For the CRS tests with the radial drainage, the value of permeability in the horizontal direction (k_h) is calculated as

$$k_h = \frac{0.762 \cdot \upsilon_p \cdot r_e^2 \cdot \gamma_w}{\overline{u}_e \cdot \overline{H}} \tag{2}$$

where υ_p = the vertical displacement rate of the specimen; r_e = the radius of the specimen; and $\overline{u}_e$ = the average excess pore water pressure at the outside perimeter of the specimen between t and $t + \Delta t$.

2.3.2 Aged Ariake clay

The values of k_v and k_h against void ratio (e) of the aged Ariake clay samples is plotted in Fig. 1. There are scatters in the test data, and for some cases k_h is initially equal to or even smaller than k_v, but all the cases show $k_h > k_v$ at the final stage (Fig. 1). While the degree of permeability anisotropy expressed as permeability ratio (k_h/k_v) generally increased with strain for all the samples (Fig. 2). The plasticity index (I_p) for samples A-1, A-2, A-3 and A-4 are 64.3, 52.4, 33.1 and 47.8, respectively. Generally, the samples with higher I_p have larger k_h/k_v ratios. With the same clay mineral, the sample with higher clay content has the higher I_p, and then it is considered that the permeability anisotropy is related to the amount of platy clay particles in the sample. The more platy clay particles, the more strain-induced permeability anisotropy will be.

2.3.3 Young Ariake clay

Fig. 3 shows the variations of k_v and k_h with e of the young Ariake clay samples. The values of k_h are obviously larger than the corresponding values of k_v. Fig. 4 shows the variations of k_h/k_v ratio with strain. For most data points, k_h/k_v ratio is approximately in the range of 1 to 5, and k_h/k_v ratio increased significantly with the vertical strain at the initial stage of deformation and it did not increase much when the vertical strain becomes larger than 15%.

2.3.4 Reconstituted Ariake clay

Fig. 5 shows the variations of k_v and k_h with e and Fig. 6 shows the variations of the k_h/k_v ratio with the vertical strain of the reconstituted Ariake clay samples. The initial k_h/k_v ratio is close to unity (Fig. 6) and the 1D deformation results in rapid increase of the k_h/k_v ratio. Another point is that the k_h/k_v ratio of the reconstituted Ariake clay samples increased faster than that of the aged Ariake clay samples with the vertical strain because the reconstituted samples almost had no inter-particles bonds and the particles can rotated freely. However, the values of k_h/k_v ratio for the reconstituted Ariake clay samples are smaller than those for the young Ariake clay samples may be because of the low clay contents, i.e., small amount of platy clay particles in the samples (Table 1).

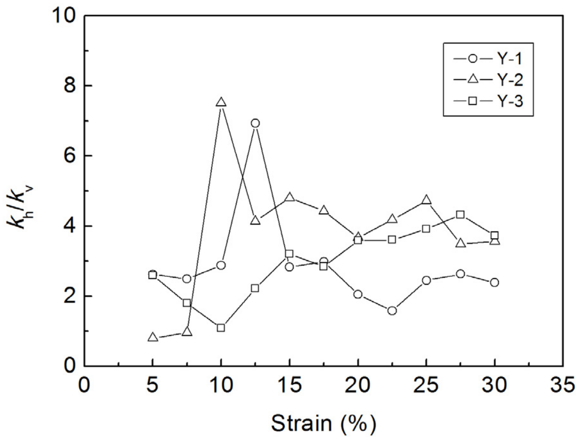


Fig. 4 Variation of permeability ratio with strain (young Ariake clay)

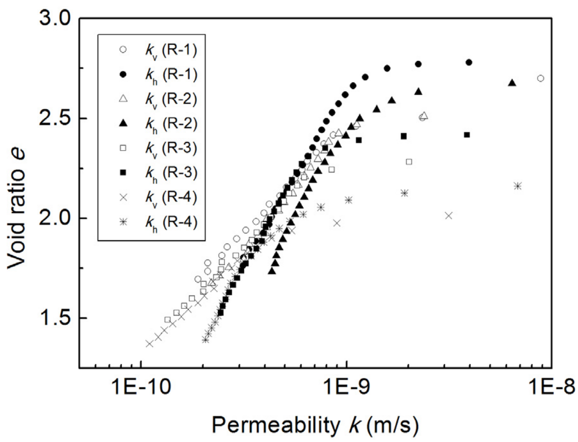


Fig. 5 Variation of permeability with void ratio (reconstituted Ariake clay)

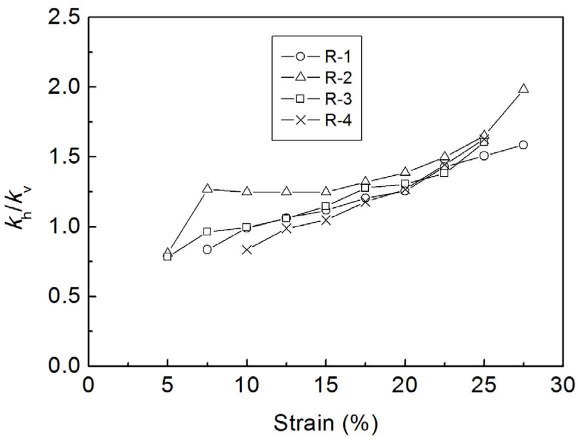


Fig. 6 Variation of permeability ratio with strain (reconstituted Ariake clay)

3. Investigation of changes in microstructure

3.1 Specimen preparation

SEM observations were made for all soil samples before and after the consolidation test on both the vertical and the horizontal planes as illustrated in Fig. 7. The axial strain after the consolidation test was about 30%. MIP tests were conducted using reconstituted soil samples only. For MIP tests, two types of rectangular cubic soil samples were used to investigate the effect of the shape of sample on MIP results, which possibly reflect the anisotropic microstructure of the sample. It is considered that if the opening sizes of the void in the vertical and horizontal planes are different, different shape of the samples will result in different pore size distributions. Let's define the area of the two horizontal faces of the sample as A_h and the area of the four vertical faces as A_v. Samples have A_v/A_h ratio larger than 1 is designated as V-sample, and less than 1 as H-sample (Fig. 7). For V-samples tested, A_v/A_h ratio is 3.5 or 4.5, and for H-samples, A_v/A_h ratio is 0.85 or 0.73. The volumes of the V-sample and the H-sample are almost the same.

The specimens for SEM observations and MIP tests were prepared by freezing-drying method. Firstly, the specimens were immersed into liquid nitrogen (-196°C) for instant freezing. Then, the frozen specimens were transferred to the vacuumed chamber of a freeze dryer (EYELA FDU-1200) for sublimation under a low temperature (-50°C) which is sustained for approximately 72 hours.

3.2 Test equipment and method

JEOL JSM-5800LV apparatus was used for SEM observation. The dehydrated specimen was fractured by finger bending to create a fresh surface for SEM observation. Then the sample was coated with gold using a JEOL JFC-1200 fine coater for 300 s to reduce the charges carried on the surface.

An AutoPore IV 9500 mercury porosimeter from Micromeritics Instrument Corporation was

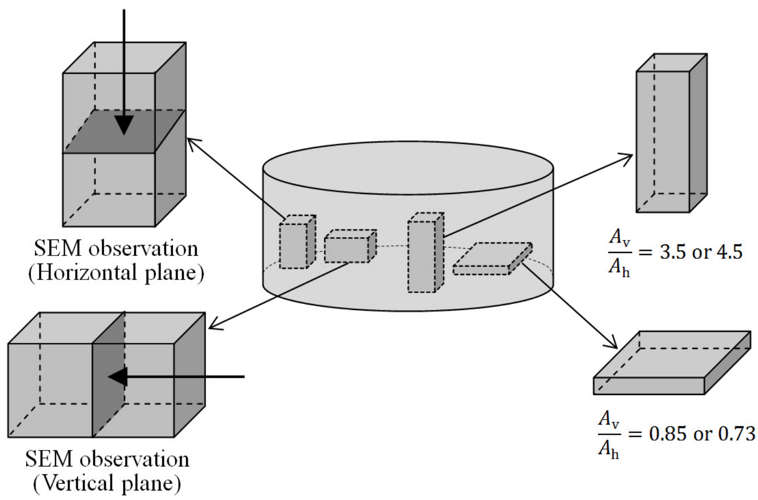


Fig. 7 Specimen preparation for microstructure investigations

used for MIP test. The MIP tests were carried out according to ASTM D4404-84 (ASTM 2004). The measurable range of pore size depends on the intrusion pressure, and pore diameters ranging from 0.008 to 470 μm were measured in this study.

3.3 Results of SEM observation

3.3.1 Aged Ariake clay

Fig. 8 shows the typical SEM images of the intact aged Ariake clay sample (A-2 sample) before and after the consolidation test. In principle we believe that the SEM images had to be interpreted in a quantitative and somehow statistical base because the area can be pictured is very small. Nevertheless, as a general tendency, it can be observed that for the intact sample, even before the consolidation test, there are more faces of platy particles on the horizontal plane (Fig. 8(b)) and more edges of platy particles on the vertical plane (Fig. 8(a)) can be seen. The difference indicates the existence of certain degree of initial anisotropic microstructure, which possibly caused by the overburden pressure. After the consolidation test, more particle edges can be observed on the vertical plane (Fig. 8(c)) and more particle faces can be observed on the horizontal

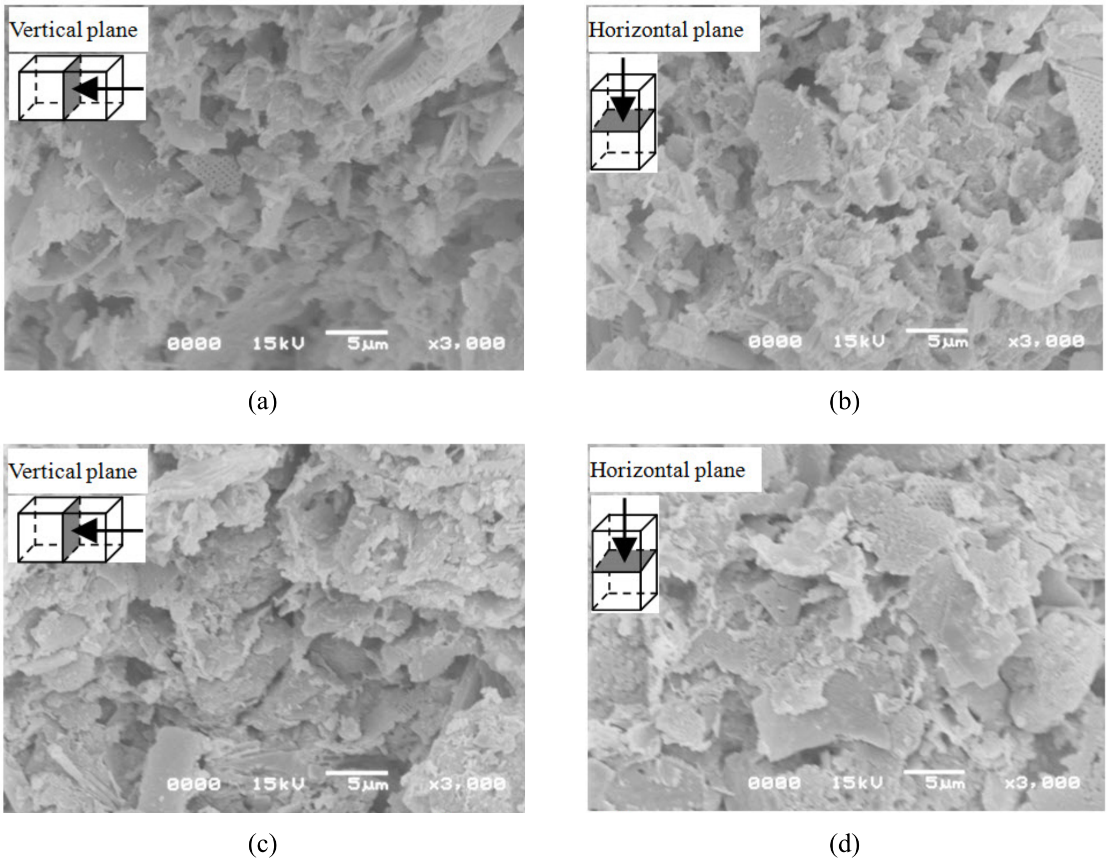


Fig. 8 SEM images of A-2 sample before and after consolidation test: (a) before, vertical plane; (b) before, horizontal plane; (c) after, vertical plane; (d) after, horizontal plane

plane (Fig. 8(d)), i.e., 1D deformation enhanced the anisotropic microstructure of the samples, and resulted in more permeability anisotropy (Fig. 2).

The k_h/k_v ratios in Fig. 2 show the gradual increase with the vertical strain, which implies gradual development of anisotropic microstructure of the intact aged Ariake clay. However, with the technique adopted in this study, the process of the development of anisotropic microstructure cannot be investigated. While, along oedometric stress paths, X-ray diffraction analyses and SEM observations highlighted the gradual development of structural anisotropy (Pusch 1970, Martin and Ladd 1975, Delage and Lefebvre 1984).

3.3.2 Young Ariake clay

Fig. 9 shows the SEM images of Y-1 sample before and after the consolidation test. Before the consolidation test (Figs. 9(a)-(b)), there is no obvious difference between the images taken on the vertical and horizontal planes, which means that the particles were randomly oriented, i.e., there was no preferential orientation. After the consolidation test, relatively, on the vertical plane, more cut edges of the particle can be seen (Fig. 9(c)), while on the horizontal plane, more platy faces of the particle of various sizes can be observed (Fig. 9(d)).

The results in Fig. 9 indicate that 1D consolidation deformation can induce particle re-orienta-

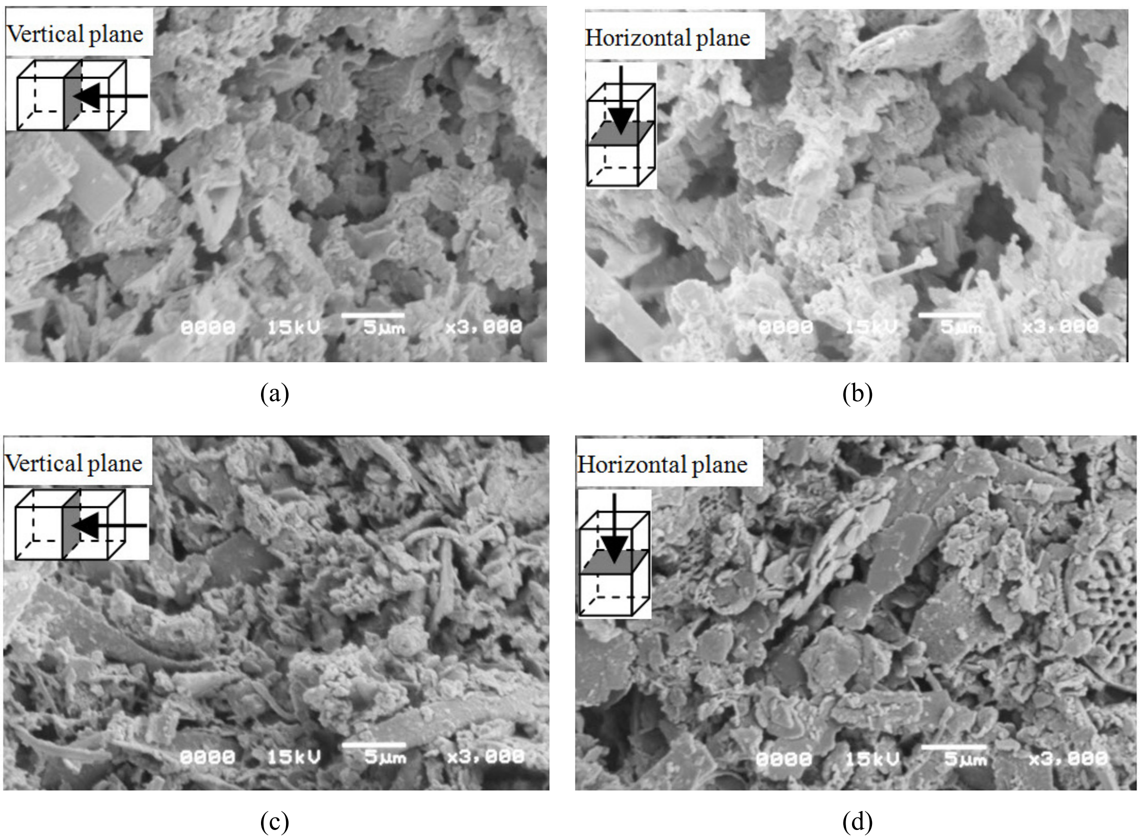


Fig. 9 SEM images of Y-1 sample before and after consolidation test: (a) before, vertical plane; (b) before, horizontal plane; (c) after, vertical plane; (d) after, horizontal plane

tion resulting in predominant horizontal oriented platy particles. It is considered that the 1D deformation induced anisotropic microstructure is the main fundamental reason of permeability anisotropy (Figs. 3 and 4). The k_h/k_v ratio increased rapidly at the initial stage of the deformation implies that the particle re-orientation might occur at the early stage of the consolidation test because of the weak inter-particle bonds of the young Ariake clay. However, SEM observations were only conducted before and after the consolidation test, and this point cannot be confirmed from SEM images.

3.3.3 Reconstituted Ariake clay

Fig. 10 shows the SEM images of R-3 sample before and after consolidation test. Figs. 10(a)-(b) show the images from the two observation planes before the consolidation test. Although the structure acquired during sedimentation was destroyed in the process of mixing, some particle edges can be observed on the vertical plane and some particle faces can be observed on the horizontal plane, which is most possibly caused by the reconstitution stress of 50 kPa. Figs. 10(c)-(d) show the images from the two observation planes after the consolidation test. On the vertical plane, relatively more particle edges can be observed, while on the horizontal plane, more

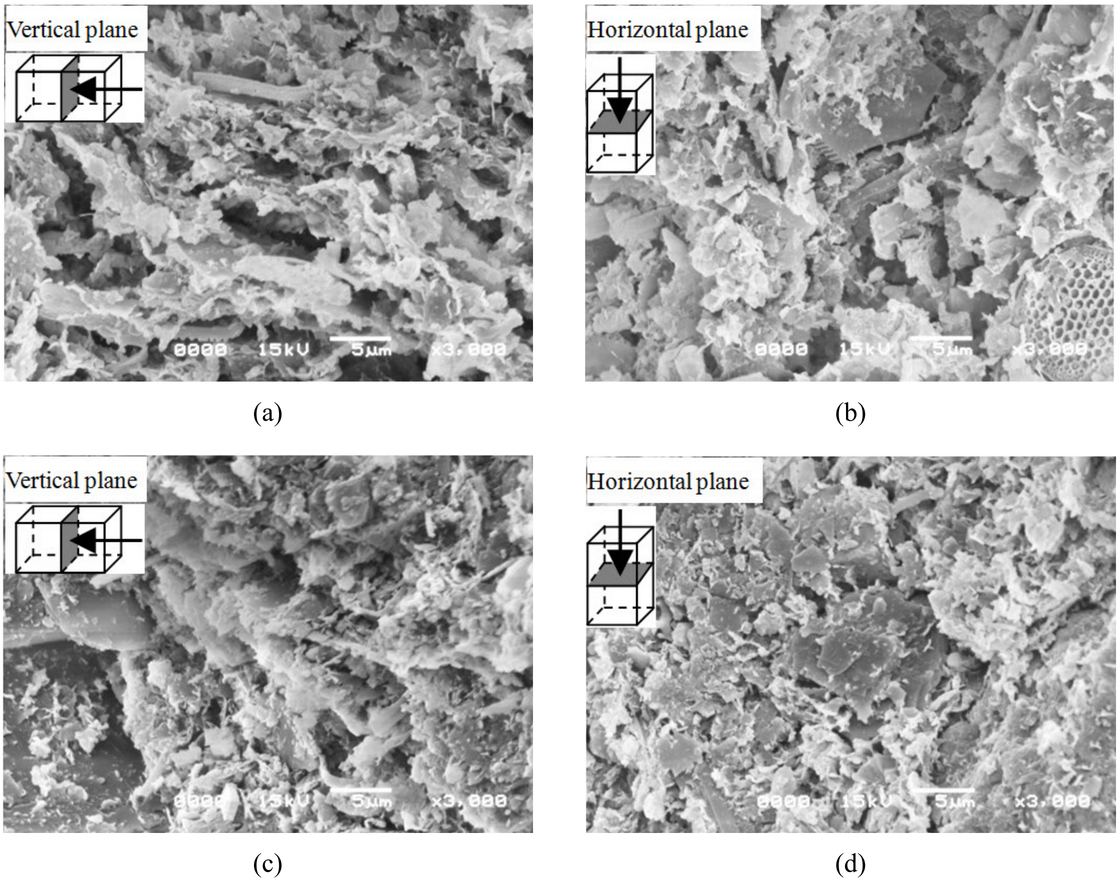


Fig. 10 SEM images of R-3 sample before and after consolidation: (a) before, vertical plane; (b) before, horizontal plane; (c) after, vertical plane; (d) after, horizontal plane

particle faces can be observed, i.e., 1D deformation enhanced the microstructural anisotropy.

3.4 Results of MIP tests

SEM images provide qualitative information about anisotropic microstructure of the clay samples. The value of permeability of soil is mainly influenced by the pore size of the sample, which can be quantified by MIP test (Diamond 1970, Griffiths and Joshi 1989, Lapierre *et al*. 1990, Kang *et al*. 2003, Tanaka *et al*. 2003, Delage 2010, Hattab and Favre 2010, Monroy *et al*. 2010). The different size and tortuosity of the pores in the vertical and horizontal directions of a sample will result in different values of permeability in the two directions. However, there are technical difficulties regarding intruding mercury from only the horizontal plane or vertical plane of a sample. The idea adopted in this study is to use samples with different ratios of the area of the vertical surfaces (A_v) to the area of the horizontal surfaces (A_h) to investigate the anisotropic microstructure of the clay samples.

For a MIP test, mercury intrusion pressure is increased stepwise, and each pressure is maintained for a time period, Δt, so called equilibrium time. Generally the equilibrium time is appreciably longer at pressures that cause an abrupt and large increase in intruded volume (ASTM 2004). Normally, Δt = 10 s is adopted as a default value. However, when Δt is long, the effect of different pore size and tortuosity will not be observed. In this study, the tests with Δt = 5 s and 10 s were conducted to study the effect of pressure increase rate on MIP test result. Fig. 11 shows the cumulative pore volume and differential pore volume (*DPV*) versus pore diameter (*D*) relations of R-1, R-2, R-3 and R-4 samples after the consolidation test with different Δt (5 s and 10 s). It can be seen that there is no obvious effect of pressure increase rate, which means the intrusion equilibrium was achieved even for Δt = 5 s. Although the data are scattered, generally the effect of the shape of the sample can be noticed. On cumulative pore volume plots, except the plot of R-2 sample, all curves show a larger cumulative pore volume of V-samples with A_v/A_h = 3.5 or 4.5. On *DPV-D* plots, V-samples resulted in obvious larger peak value than H-samples for R-1 sample. While for R-2, R-3 and R-4 samples, they are practically the same. These results indicate that mercury can be intruded into the sample from the vertical plane more easily than that from the horizontal plane, which indirectly confirms the existence of anisotropic microstructure of the samples. However, for some cases, the difference between V-sample and H-sample is not very clear, which indicates that the technique used may have limited capacity to identify the microstructure anisotropy of soil sample.

4. Discussions

The Ariake clays exhibit permeability anisotropy and it is believed mainly due to the anisotropic microstructure with a predominant horizontal orientation of platy clay particles. Under odometer condition, the degree of permeability anisotropy increased with the vertical strain indicates that 1D deformation caused re-orientation of platy clay particles. However, the permeability anisotropy and the development of the permeability anisotropy with the vertical strain are different for the three types of the Ariake clays tested. There is a clear effect of initial inter-particle bonds and clay content on the permeability anisotropy induced by 1D deformation.

Comparing the k_h/k_v ratios of the aged and the young Ariake clay samples, a noticeable difference is the increase rate of k_h/k_v with the vertical strain. For the young Ariake clay, k_h/k_v ratio

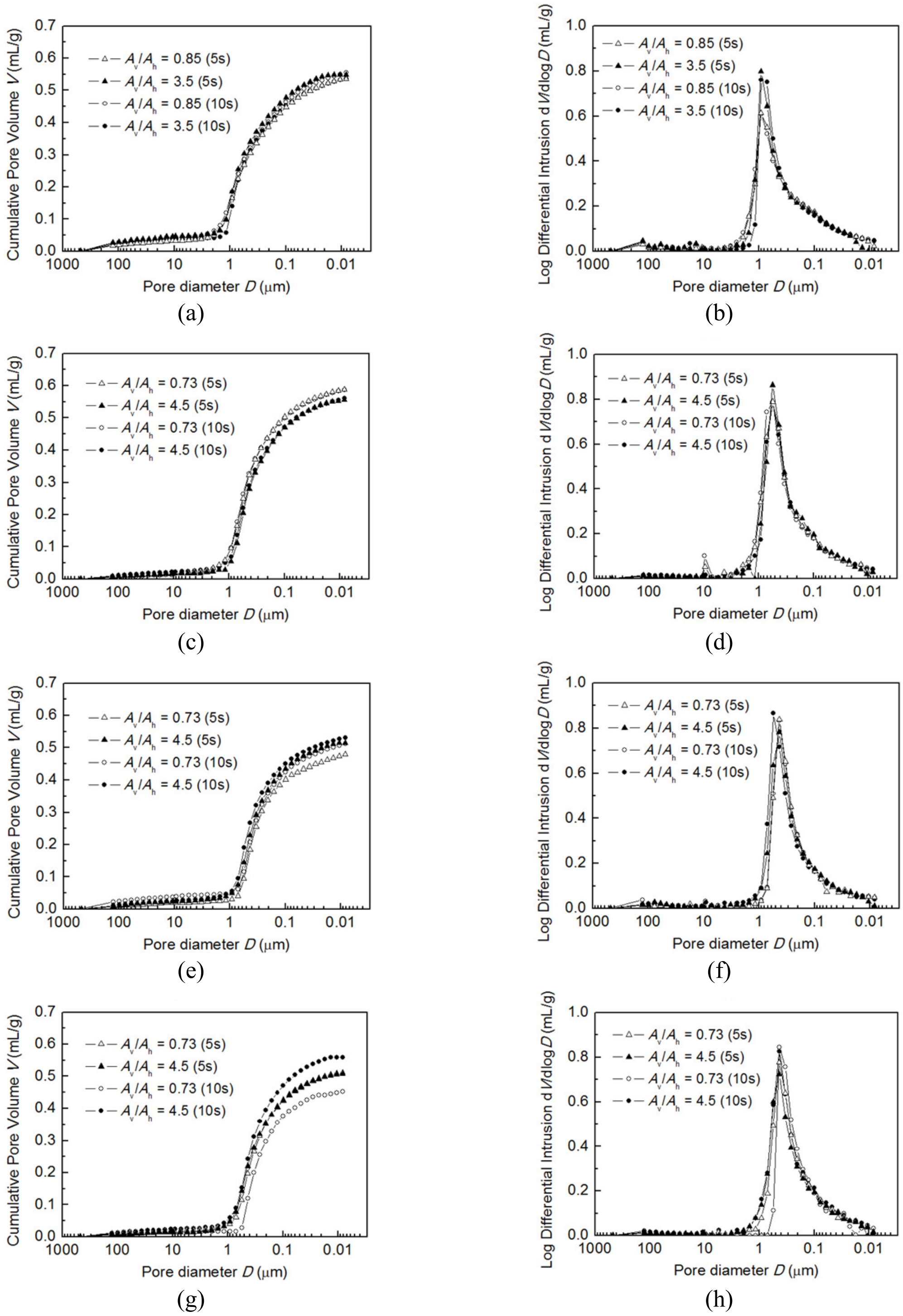


Fig. 11 Cumulative pore volume distributions and differential pore volume distributions of reconstituted Ariake clay samples after consolidation: (a), (b) R-1 sample; (c), (d) R-2 sample; (e), (f) R-3 sample; (g), (h) R-4 sample

increased much faster than that of the aged Ariake clay for the vertical strain less than about 15%. After that k_h/k_v ratio was kept practically almost unchanged. While for the aged Ariake clay, although the data are scattered, the increase rate of k_h/k_v was not changed much up to about 30% the vertical strain. Among the differences between the two clays, one difference is the inter-particle bonds. The increase rate of k_h/k_v is related to the re-orientation rate of the particles. The aged Ariake clay had stronger inter-particle bonds which can partially restrict the rotation of the particles before they were broken. As a result, the permeability anisotropy developed slowly associated with gradual yielding of the soil sample. The young Ariake clay had weaker inter-particle bonds which can be broken easily, and thus the particles can rotate easily with 1D consolidation deformation. It is postulated that at a vertical strain of about 15%, most soil particles already reached their final position in term of orientation.

Since the permeability anisotropy is resulted from predominant orientation of platy clay particles in certain direction, it is very natural to think that the permeability anisotropy may be related to the types of clay mineral and clay content. For the young and the reconstituted Ariake clay samples tested, the clay minerals are about the same, but the clay contents are different. The young Ariake clay had higher clay content (Table 1), and the k_h/k_v values were higher, even the inter-particle bonds of the young Ariake clay may be slightly stronger than that of the reconstituted Ariake clay. For the aged Ariake clay, the samples with higher clay contents also show higher k_h/k_v values.

5. Conclusions

The one-dimensional (1D) deformation induced permeability anisotropy has been investigated using three types of Ariake clays by constant rate of strain (CRS) consolidation tests, scanning electric microscopy (SEM) images and mercury intrusion porosimetry (MIP) tests. The three types of the samples are aged Ariake clay (clay deposited in Saga plain), young Ariake clay (clay deposited in the seabed of Ariake Sea) and reconstituted Ariake clay. Based on the test results, the following conclusions can be drawn:

- For all soil samples tested, permeability in the horizontal direction (k_h) deduced from CRS consolidation test is larger than that in the vertical direction (k_v), i.e., exhibiting anisotropic permeability behavior. The degree of the permeability anisotropy increased with 1D consolidation deformation. SEM images and pore size distributions from the MIP tests confirmed the existence of 1D deformation induced anisotropic microstructure, i.e., a predominant horizontal orientation of platy clay particles. Therefore, the permeability anisotropy is the result of the anisotropic microstructure of the samples.
- Development of anisotropic microstructure, and therefore, anisotropic permeability is influenced by initial inter-particle bonds. For the aged Ariake clay, because of existence of stronger initial inter-particle bonds, which restricted re-orientation of the clay particles, the development of permeability anisotropy was slower than those of the young and the reconstituted Ariake clays. For the young Ariake clay, the permeability anisotropy increased faster at the initial stage of 1D deformation because of initial weaker inter-particle bonds.
- Although it may be not conclusive, it seems that the permeability anisotropy is related to the amount of clay content. The young Ariake clay had higher clay content, resulting in higher k_h/k_v values than those of the reconstituted Ariake clay, even the inter-particle bonds of the young Ariake clay may be slightly stronger than that of the reconstituted Ariake clay. For

the aged Ariake clay, the samples with higher clay contents also show higher values of k_h/k_v.

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