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Influence of sand fraction on compressibility and hydraulic conductivity of clayey soils

Influence de fraction de sable sur la compressibilité et conductivité hydraulique des sols argileux

Y. Watabe
Port and Airport Research Institute, Yokosuka, Japan
K. Saitoh
Chuo-University, Tokyo, Japan

ABSTRACT
For mixtures of a dredged clay and a sand in various ratios, the compressibility and the hydraulic conductivity were investigated by carrying out the incremental loading consolidation test (oedometer test), scanning electron microscopic observation (SEM), and mercury intrusion porosimetry test (MIP), in consideration of influence of sand fraction on the compressibility and the hydraulic conductivity. The followings were derived as conclusions: If the sandy particles do not make a skeletal structure and each particle independents in the clay matrix, increasing sand fraction contributes to decrease the compressibility, but does not affect on the hydraulic conductivity, under the same overburden stress. In this study, some evidences of sandy skeletal structure were observed in the specimens, whose clay (less than 0.005 mm) and sand (larger than 0.075 mm) fractions are smaller than 16.5% and larger than 68.6%, respectively.

RÉSUMÉ
Pour des mélanges d'un argile dragué et d'un sable dans divers rapports, la compressibilité et la conductivité hydraulique ont été étudiées en effectuant l'essai de consolidation par accroissement de chargement (essai d'oedometer), l'observation à microscope électronique de balayage (SEM), et l'essai porosimetry d'intrusion de mercure (MIP), dans la considération de l'influence de la fraction de sable sur la compressibilité et la conductivité hydraulique. La suite a été dérivée comme conclusions: Si les particules arénacées ne font pas une structure squelettique et des indépendants de chaque particules dans la matrice d'argile, la fraction croissante de sable contribuent pour diminuer la compressibilité, mais n'affectent pas sur la conductivité hydraulique, sous le même effort de terrains de recouvrement. Dans cette étude, on a observé quelques évidences de structure squelettique arénacée dans les spécimens, dont la fraction d'argile (moins de 0.005 mm) et la fraction de sable (plus en grande partie que 0.075 mm) soyez plus petit que 16.5% et plus en grande partie que 68.6%, respectivement.

1 INTRODUCTION

Most waste landfill sites along the coast are on natural clay deposits which play a role as a bottom hydraulic barrier; however, some are on a sandy layer with artificial hydraulic barrier. The performance as the hydraulic barrier should be reliably evaluated in consideration of the influence of sand faction on the hydraulic conductivity. When a clayey artificial hydraulic barrier (Yamada et al., 2003) is placed on a sandy seabed, the dredged clay is generally not uniform and shows a certain level of variation of sand fraction. In addition, since increasing sand fraction at the same water content results high fluidity and low compressibility, thus adding some amount of sand into the dreaded clay is valuable to either improve the pumping efficiency or control the consolidation settlement. Hydraulic conductivity is generally a function of pore entrance size distribution (Marshall, 1958) which is strongly influenced by the grain size distribution (i.e. sand fraction). In this study, influence of the sand fraction on the performance as a hydraulic barrier was investigated through oedometer test and microscopic observation.

2 SAMPLE PREPARATION

The clay used in this study is Nagoya clay, which has passed a sieve of 2 mm, with particle density ρ_s of 2.672 g/cm^3, liquid limit w_L of 62.6% and plasticity index I_p of 30.7. An observed SEM image of a reconstituted sample consolidated under 49 kPa is shown in Figure 1, indicating that microfabric consisted of both clay and silt is very homogeneous. The sand fraction is adjusted by adding Niigata sand, with particle density ρ_s of 2.687 g/cm^3, maximum void ratio e_{max} of 1.096 and minimum void ratio e_{min} of 0.660. An observed SEM image of the sand is shown in Figure 2, indicating that the sand particles are round shaped.

The water content of the clay was adjusted to twice of liquid limit $2w_L$ (=130%), and 9 mixtures of clay with sand in dry mass percentage of 10:0 to 10:40 were prepared. Physical properties of these mixtures are summarized in Table 1 and those grain-size distribution curves are shown in Figure 3, where the curves for 10:1 to 10:5 are calculated from the grain-size distribution curves for both Nagoya clay and Niigata sand. Sand frac-

Table 1: Physical properties of clay and sand mixtures

		10:0	10:1	10:2	10:3	10:4	10:5	10:10	10:20	10:40	Sand
Particle density ρ_s	g/cm^3	2.672	2.673	2.675	2.675	2.676	2.687	2.680	2.682	2.684	2.687
Gravel fraction	%	0.0	1.3	2.4	3.4	4.2	4.9	ND	ND	ND	14.6
Sand fraction	%	5.5	13.9	21.2	27.1	32.1	36.5	52.8	68.6	78.0	84.2
Silt fraction	%	55.5	49.4	44.2	39.7	36.0	32.6	25.2	14.9	13.0	1.2
Clay fraction	%	39.0	35.4	32.2	29.8	27.7	26.0	22.0	16.5	9.0	0.0
Liquid limit w_L	%	62.6	53.9	49.7	45.9	42.1	36.8	31.3	25.9	21.7	NP
Plastic limit w_p	%	31.9	27.5	27.1	22.8	22.6	22.0	NP	NP	NP	NP
Plasticity index I_p		30.7	47.9	26.4	22.6	23.1	19.5	NP	NP	NP	NP
Adj. water cont. $2w_L$	%	130	98	94	90	80	76	68	48	32	NP

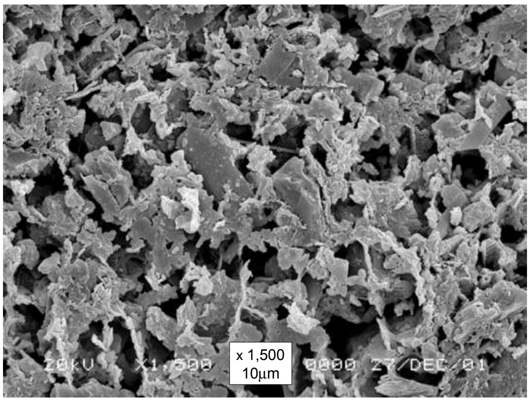

Figure 1. Microfabric of Nagoya clay

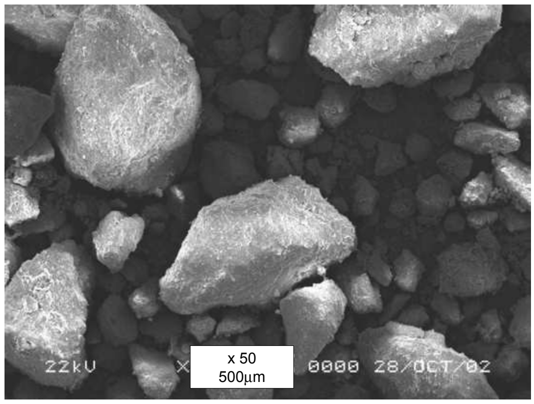

Figure 2. Sand particles of Niigata sand

tions of Nagoya clay and the mixtures of 10:10 and 10:40 are 5.5%, 52.8% and 78.0%, respectively.

The mixtures of 10:0 to 10:40 were placed into a mold in an adjusted water content of $2w_L$, respectively, and preliminarily consolidated under a pressure of 49 kPa. Then, the samples were trimmed into a size of 60 mm in diameter and 20 mm in height for the oedometer test.

3 TEST PROCEDURE

In this study, the 24 hours incremental loading oedometer test (JIS A 1217) was carried out to investigate the influence of sand fraction on the compressibility and the hydraulic conductivity. This test corresponds to consolidation of a bottom hydraulic barrier caused by dumped wastes. The pressures applied to the specimen were from 9.8 kPa to 1256 kPa, in total 8 stages, with incremental loading ratio $\Delta p/p$ of unity. Hydraulic conductivity k of a clayey soil is generally obtained from both the coefficient of consolidation c_v and the coefficient of volume compressibility m_v. In this study, k was calculated from these two parameters.

Since the hydraulic conductivity is strongly influenced by the microfabric, mercury intrusion porosimetry test (MIP) to evaluate the pore entrance size distribution and scanning electron microscope (SEM) observation were carried out. The specimens had to be dried without volume change in order to avoid the damaged microfabric. In this study, freeze-cut-drying method (Watabe et al., 2004) was adopted. A trimmed small sample was dropped into the liquid nitrogen (boiling point at -196^oC) in order to freeze it instantly without crystallized ice, and divided into two pieces by tension crack to make a flat observation plane in a vertical section. The ice was sublimed under the vacuum.

4 TEST RESULTS AND DISCUSSION

Relationships between void ratio e and logarithmic consolidation pressure p are shown in Figure 4. In the vertical axis, both the minimum and the maximum void ratios (e_{min} and e_{max}) of Niigata sand are indicated. Void ratio e decreases with increasing sand fraction; e.g. e for mixtures of 10:5 and 10:20 becomes to respectively 65% and 40% of that for the original Nagoya clay (10:0). This fact can be explained as follows: some parts of clay matrix consisted of both clay particles and pores are replaced by solid sand particles. Comparing 10:20 and 10:40, however, void ratio e does not change even though sand fraction becomes twice. If sand fraction of the mixture is larger than 10:5, sand particles possibly make a skeletal structure, since the initial void ratio is smaller than e_{max}. In the cases of 10:20 and 10:40, which have an initial void ratio smaller than e_{min}, sand particles should make a skeletal structure and there is not enough amounts of clay particles to fill up the pores between sand particles. In the case of 10:40, because of its small compressibility, its void ratio becomes slightly larger than that of 10:20 under a higher consolidation pressure.

Variation of compression index C_c with sand fraction is shown in Figure 5. Compressibility represented by compression index C_c decreases when sand fraction increases. Compression index C_c decreases linearly with sand fraction for 10:0 to 10:20, but C_c of 10:40 is almost the same as that of 10:20. This fact indicates that the consolidation characteristics are governed by sand structure when sand fraction is larger than that of 10:20.

Relationships between void ratio e and logarithmic hydraulic conductivity k are shown in Figure 6. Also, relationships between logarithmic hydraulic conductivity k and logarithmic mean consolidation pressure p are shown in Figure 7. In these

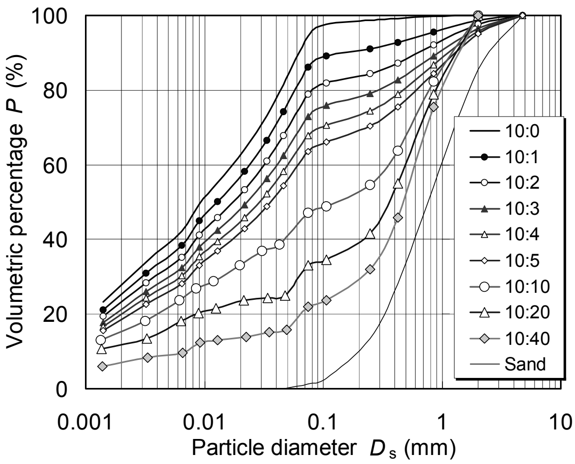

Figure 3. Grain size distribution curves

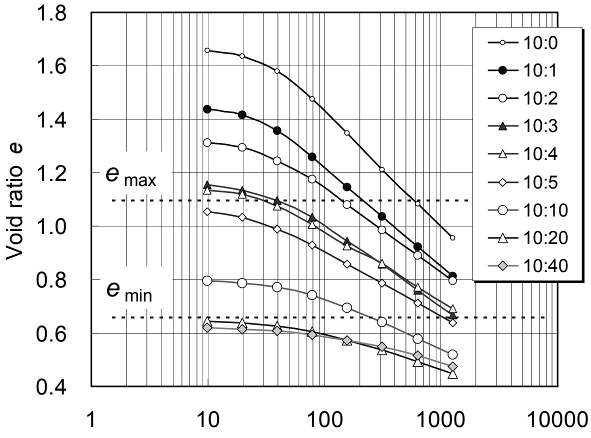

Figure 4. e—log p relationships

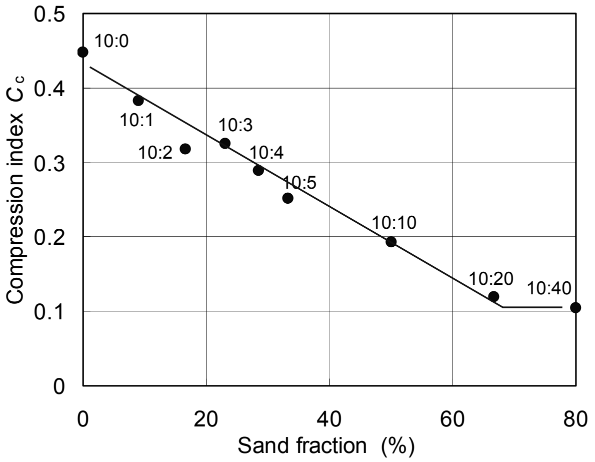

Figure 5. Relationships between compression index and sand fraction

figures, the data in normal consolidation; where p is larger than 55.5 kPa, are plotted. Under a certain value of void ratio, hydraulic conductivity k can take various values, and it increases with sand fraction. On the other hand, in the cases of 10:0 to 10:10, a unique log k—log p relationship, which is not a function of sand fraction, is obtained. Under a certain consolidation pressure, thus, hydraulic conductivities for these cases show almost the same value. This fact indicates that the hydraulic conductivity is governed by the clay matrix in these cases. In the cases with sand fraction larger than 10:20, however, the hydraulic conductivity increases with sand fraction; e.g. the hydraulic conductivity for 10:40 becomes more than 10 times larger than the others. These tendencies are consistent with e—log p curves in consideration of e_{min}, as shown in Figure 4. From the test results described above, adding sand up to 10:10 does not affect on the hydraulic conductivity but contribute to decrease consolidation settlement, for the materials dealt in this study.

Volumetric pore entrance size frequency distributions obtained from MIP test for the mixtures consolidated under 49 kPa are shown in Figure 8. The peak on the pore entrance frequency distributions significantly decreases with sand fraction increases. Pore entrance diameter at the peak increases with sand fraction, as 0.0006 mm for 10:0 and 0.0015 mm for 10:40. In the case of 10:40, another peak appears at a pore entrance diameter of around 0.008 mm.

Variations of pore volume for (a) before and (b) after consolidation corresponding to six pore-size groups per unit mass (1 g) of soil particles associated with mixtures of 10:0, 10:10, 10:20 and 10:40 are shown in Figure 9. Sand fraction is the larger, pore volume is the smaller. Pore volume corresponds to an entrance diameter smaller than 0.0001 mm is essentially constant before and after the consolidation. In the cases of 10:0 and 10:10, pore size range of 0.001 mm < D_p < 0.01 mm is dominant before consolidation; however, pore size range of D_p < 0.001 mm is dominant after consolidation. This fact means that a large pore was compressed, but remains as small pores. When sand fraction is higher than 10:20, sand particles possibly make a skeletal structure since initial void ratio is smaller than e_{min} (see Figure 4). This is consistent with the sand fraction at which hydraulic conductivity significantly increases (see Figure 7).

Observed SEM images for specimens after consolidation are shown in Figure 10. Figure 10*a* is a SEM image of 10:10 observed with a magnification of 50 times, and Figure 10*b* observed with a magnification of 1500 times is an enlarged part indicated by an arrow in Figure 10*a*. Figure 10*c* and *d* is observed with a magnification of 50 times for 10:20 and 10:40, respectively. In Figure 10*a* and *b*, sand particles do not make a skeletal structure and each particle independents in the clay matrix; but interface between a sand particle and the clay matrix are perfectly in touch. In the case of 10:10, an aspect on consolidation behavior is governed by the clay matrix as indicated

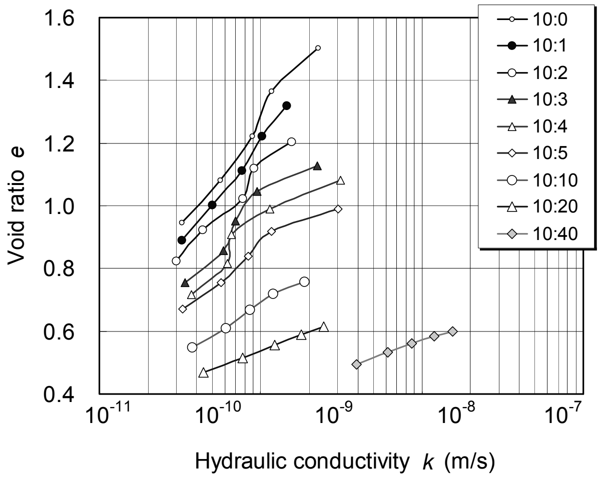

Figure 6. e—log k relationships

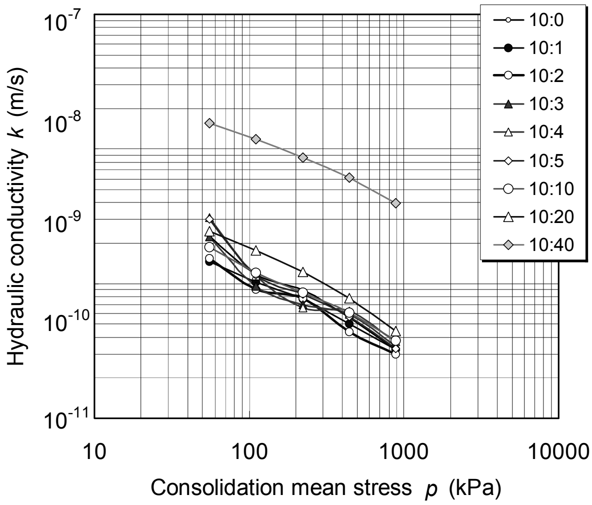

Figure 7. log k—log p relationships

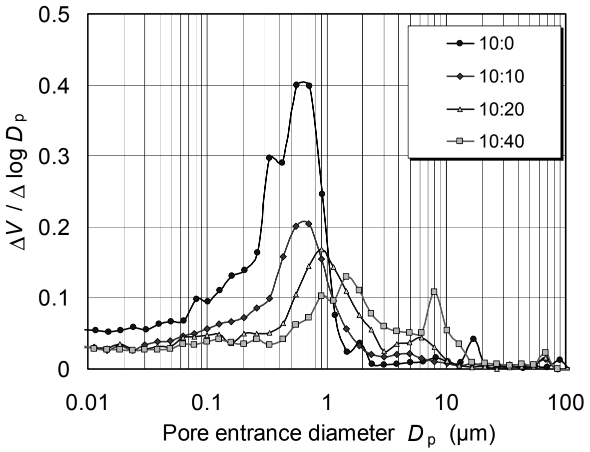

Figure 8. Pore entrance size frequency distributions

in consolidation test result; however, its void ratio is very small because of a large sand fraction. Therefore, it can be said that the mixture 10:10 shows characteristics as not only sand but also clay. In Figure 10*c* and *d*, sand particles contact each other making a skeletal structure.

In the cases of 10:20 and 10:40, since clay particles mainly fill up large pores between sand particles, a skeletal structure consisted of sand particles results small compressibility. In consideration of the small void ratio and the skeletal sand structure, the large pores between the sand particles in the mixture 10:40

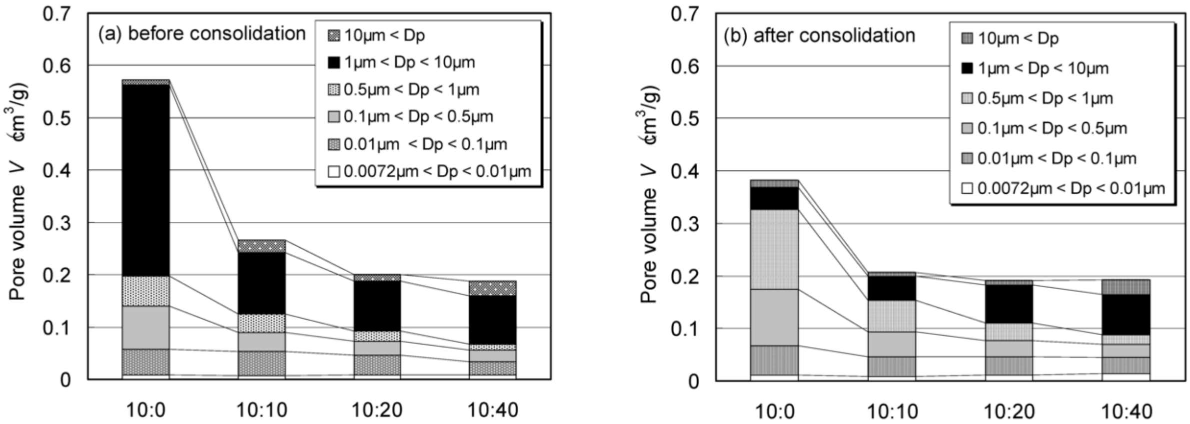

Figure 9. Pore entrance size frequency (a) before consolidation test and (b) after consolidation test

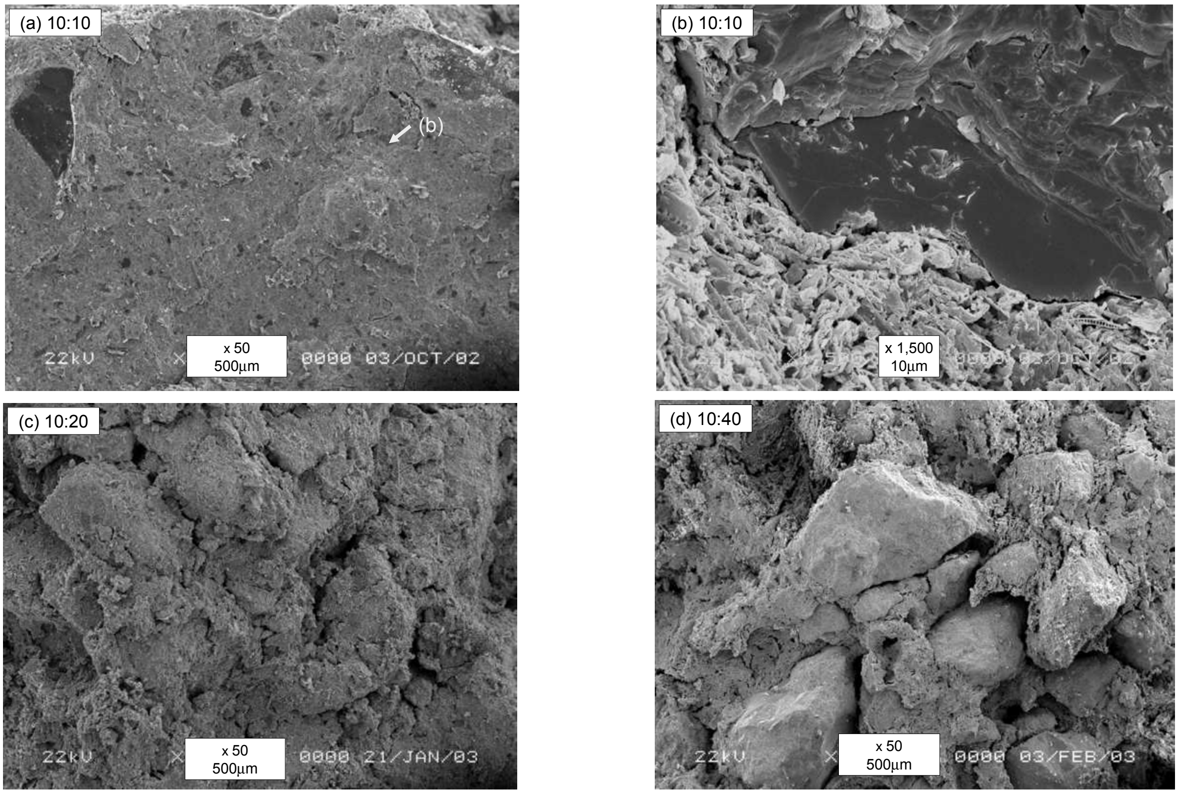

Figure 10. Observed SEM images

are unfilled with the clay matrix. Thus, pore entrance size frequency distribution in Figure 8 shows a relatively large value at a size of around 0.008 mm. Therefore, the hydraulic conductivity of 10:40 becomes more than 10 times larger than that of the original clay.

5 CONCLUSIONS

If the sand particles do not make a skeletal structure and each particle independents in the clay matrix, increasing sand fraction contributes to decrease consolidation settlement, but does not affect on the hydraulic conductivity. Almost the same hydraulic conductivity was obtained at the same consolidation pressure from the oedometer tests for the mixtures 10:0 to 10:10. When sand fraction is higher than 10:20, sand particles make a skeletal structure, and the large pores between the sand particles are unfilled with the clay matrix. Thus it results a high hydraulic conductivity. In this study, some evidences of skeletal sandy structure were observed for the mixtures 10:20 and 10:40. The mixture 10:20 corresponds to clay (smaller than 0.005 mm) and sand (greater than 0.075 mm) fractions of 16.5% and 68.6%, respectively.

When dredged clay is pumped to place on the seabed of waste reclamation site as a hydraulic barrier, increasing sand fraction is possibly a good solution in order to control the consolidation settlement. However, the sand fraction shall be strictly limited not to affect on the hydraulic conductivity.

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