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Consolidation Characteristics Analysis of the Busan Region Dredging Clay

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Abstract: The purpose of this study is to understand characteristics of marine clay in the Busan Region by calculating dynamic and consolidation characteristics of dredging reclamation clay in the region and the relationship among void ratio-effective stress-permeability coefficient through self-weight consolidation based on a centrifugal model test. In the study, a standard consolidation experiment was conducted to calculate Compression index (C_c) and permeability Change index (C_k) for the purpose of understanding consolidation characteristics of the sample at a low void ratio. According to the result of the self-weight consolidation experiment, the representative constitutive equation was $e = 2.8\sigma'^{-0.142}$, $k = 1.62\times10^{-5}\, e^{4.82}$. Also, the bulking factor calculated by using PSDDF (Primary consolidation, Secondary compression, and Desiccation of Dredged Fill) converged toward 1.083-1.266 at the finish point of self-weight consolidation.

Key words: Dredging reclamation clay, constitutive equation, bulking factor, void ratio-effective stress, void ratio-permeability, finite strain consolidation

INTRODUCTION

The dredging construction is for marking reclaimed land by dredging marine clay with seawater and then bringing the dredged soil into the reclaimed land. It is inevitable to dredge and dumping marine clay in reclaimed land created by dredging reclamation, considering the supply and economic feasibility (Anonymous, 2005). Spoil that has been excavated during harbor construction in general has high levels of moisture content and widely varying engineering characteristics according to the region. Particularly in the Southern Sea region in which the main component of spoil is clay the spoil has highly different sedimentation and self-weight consolidation characteristics as well as basic properties such as particle size distribution and plasticity index from those of spoil in the Western Sea Region where the spoil mainly consists of silt and sand (Kim, 2009). Also, due to engineering behaviors that are different from natural ground marine clay, the consolidation settlement is relatively high. As a result, sedimentation and consolidation behaviors that determine spoil settlement are critical design factors when calculating required amount of dredging and predicting short and long-term settlement in reclaimed land and therefore, must be accurately predicted. In the past, the designs and constructions were carried out only for the purpose of containment area and therefore, reliable design data for analyzing spoil sedimentation and consolidation is limited. Also, it is difficult to find data related to the type of spoil that was dumped during construction or relevant log. Nonetheless, prior to proceeding with dredging and reclamation, it is necessary to conduct laboratory test and numerical analysis in order to understand sedimentation and self-weight consolidation of the relevant spoil and thereby, predict self-weight consolidation and bulking factor, among others with time. In this study, spoil in the Busan New Port was used to conduct basic properties, standard consolidation, Constant Rate of Strain (CRS) and centrifugal model tests. We obtained the constitutive relationship of void ratio, effective stress and permeability coefficient in spoil with high moisture content by applying the finite strain consolidation theory. Based on the result we calculated the self-weight consolidation settlement and bulking factor with time in the reclaimed land and proposed conditions that are expected after dumping spoil on the site, so that, they can be applied in actual design process in future projects.

MATERIALS AND METHODS

Analysis of dredging reclamation clay characteristics

Characteristics of Busan Region clays: To analyze physical and consolidation characteristics of the dredging reclamation clay we conducted basic physical properties, standard consolidation and CRS consolidation tests. Pump dredger which is widely used in dredging reclamation of marine clay in South Korea is completely

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Table 1: Physical properties of Buasn Region clays

Sections	Specific Gravity (Gs)	Liquid Limits (LL) (%)	Plastic Limits (PL) (%)	Plastic Index (PI)	Activity (AC)	Passing #200 (%)	Clay particle <2 μm (%)	USCS
F1	2.712	59.63	16.72	42.91	1.7	99.10	24.70	CH
F2	2.719	53.80	15.90	37.95	1.8	98.98	21.23	CH
F3	2.710	54.43	17.43	37.00	1.6	97.24	22.63	CH
F4	2.713	51.35	23.23	28.12	1.0	98.50	28.52	CH
F5	2.707	54.08	17.61	36.47	1.3	96.56	28.87	CH
F6	2.714	53.45	24.71	28.74	1.2	95.26	24.36	CH

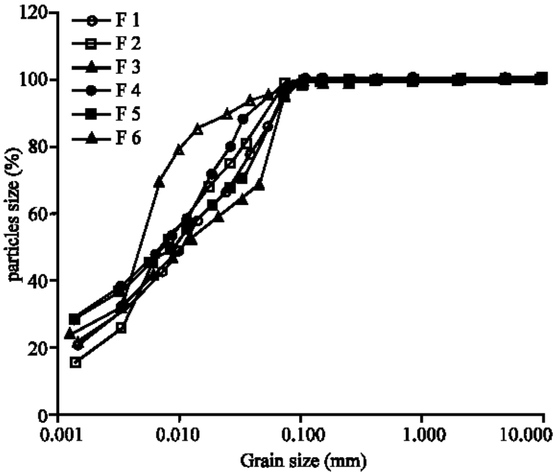

Fig. 1: Particle size distributions

disturbed by using cutter before it is mixed with water and added to reclaimed land. Therefore, we collected disturbed sample and applied it to the laboratory test and centrifugal model test. Characteristics of dredging clay in the Busan Region were analyzed based on samples collected from six dredging reclamation sites in Busan. Regarding the dredging reclamation clay, we analyzed the specific gravity, liquid and plastic limits and fineness number (sieve analysis, #200 sieve passage test, hydrometer analysis) the result of which is shown in Table 1. The relevant grading curve and plasticity chart are presented in Fig. 1-3. The specific gravity of dredging reclamation clay collected in Busan ranged between 2.707 and 2.719 with the average being 2.713. The average liquid limit was 54.46%, average plastic limit 19.27% and average plasticity index 35.20.

The percentage passing #200 sieve was over 97.61% and the clay particle content was between 21.23 and 28.87%. The clay activity was on average, 1.43, ranging between 1.0 and 1.8 which is relatively high. Clay samples collected in Busan had liquid limits below 60%, mostly concentrated between 50 and 59%. Also, the sample clay activity chart shows that active clay is formed close to A = 1.25.

Table 2: Consolidation properties

Variables	F1	F2	F3	F4	F5	F6
C_c	0.642	0.426	0.536	0.588	0.573	0.510
C_k	0.967	0.850	0.922	1.014	0.944	0.765

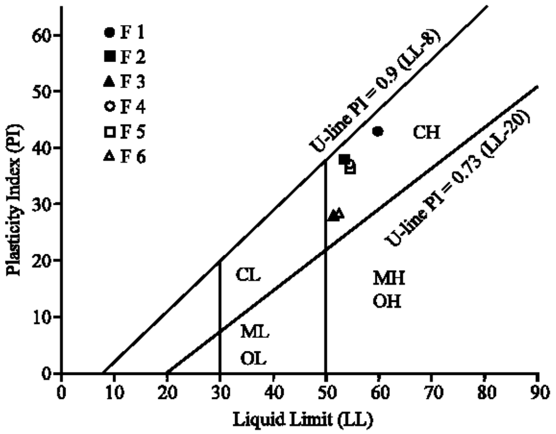

Fig. 2: Plasticity chart

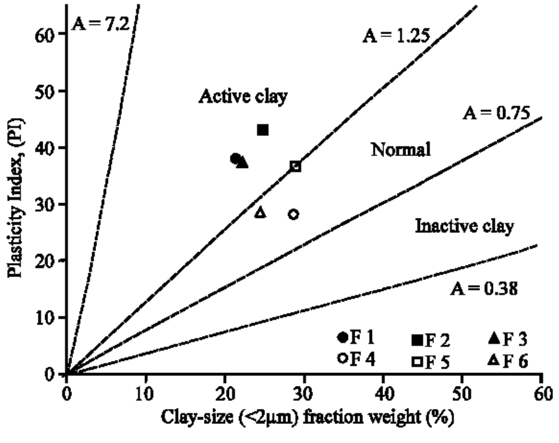

Fig. 3: Activity chart

Consolidation characteristics analysis: To analyze consolidation characteristics, we conducted standard consolidation and CRS consolidation tests and the results are shown in Fig. 4 and 5, respectively. Figure 4 and 5 show the relationship between void ratio and effective stress and that between void ratio and permeability coefficient at low void ratio.

Table 2 shows Compression index (C_c) and permeability Change index (C_k) from the standard consolidation test results. Here, C_c and C_k are the mean

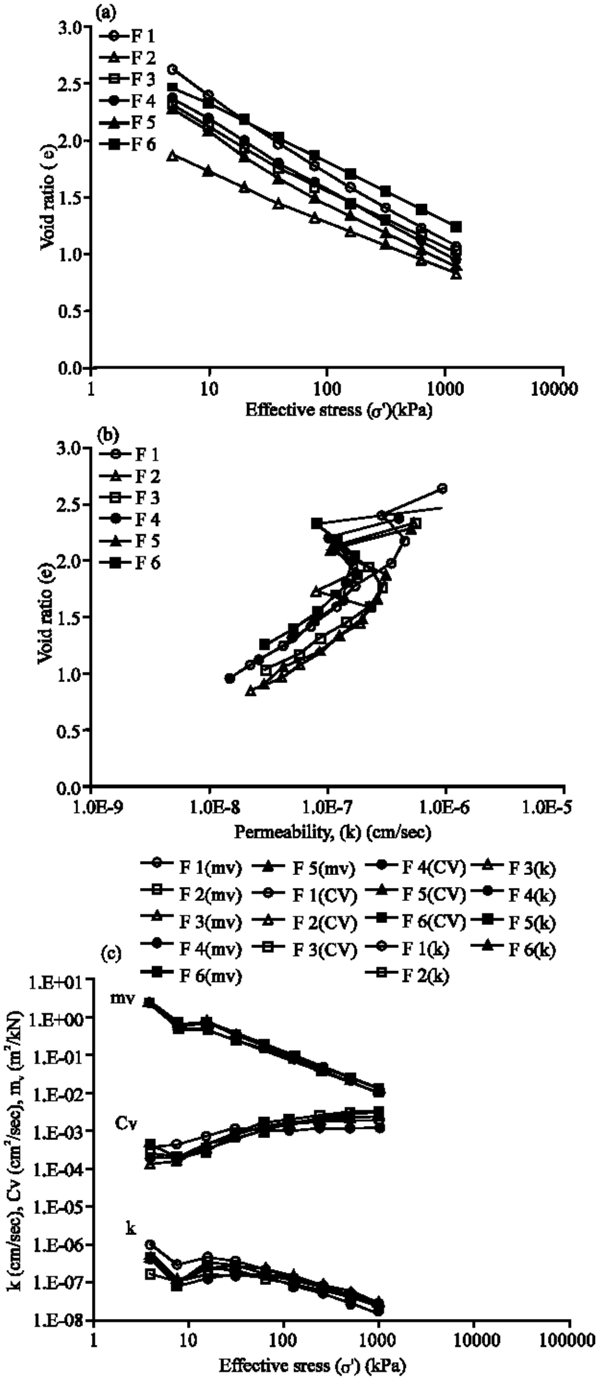

Fig. 4: Results of standard consolidation test; a) Void ratio-effective stress (e-log `σ); b) Void ratio-permeability (e-log k); c) Trend of consolidation properties (C_v, m_v, k)

$$C_k = \frac{e_0 - e_1}{\log k_0 - \log k_1} \qquad (1)$$

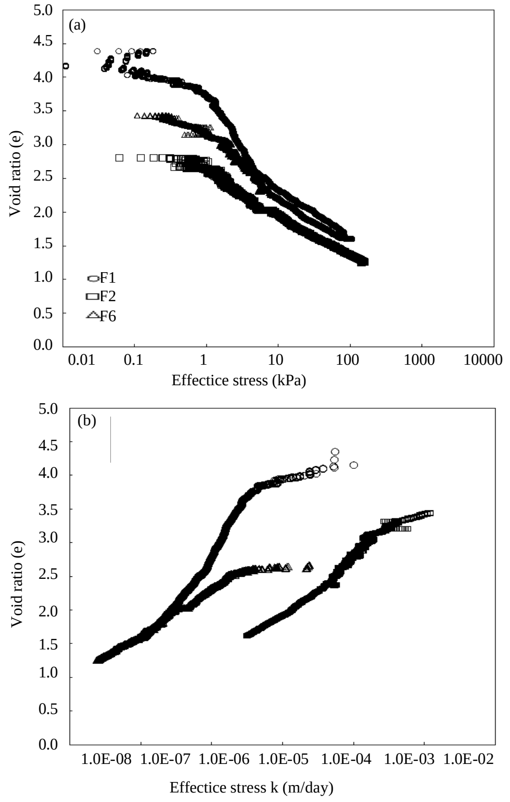

Fig. 5: Results of CRS consolidation test; a) Void ratio-effective stress (e-log σ′); b) Void-permeability (e-log k)

value of each dredging clay and the permeability change index is defined as Eq. 1. In the standard consolidation test, overall as the consolidation load increases, so did the consolidation coefficient.

Figure 4c shows change of the Consolidation coefficient (C_v), volume change coefficient (m_v) and permeability coefficient (k). Although, Mikasa (1965) (Somgyi, 1979) assumes that in Terzaghi's consolidation theory, the permeability coefficient, volume change coefficient and consolidation coefficient do not change during the consolidation process when the permeability coefficient was small, so was the volume change coefficient and by contrast when the permeability coefficient was large, so was volume change coefficient. Volume change coefficient tended to decrease when consolidation load increased. Also, when the volume change coefficient decreased, so did the permeability coefficient.

Figure 5 shows the result of void ratio (e)-effective stress (log p′) analyzed based on the CRS consolidation test and Fig. 6 the result of void ratio (e)-permeability coefficient (log k). As shown in figure, the range was

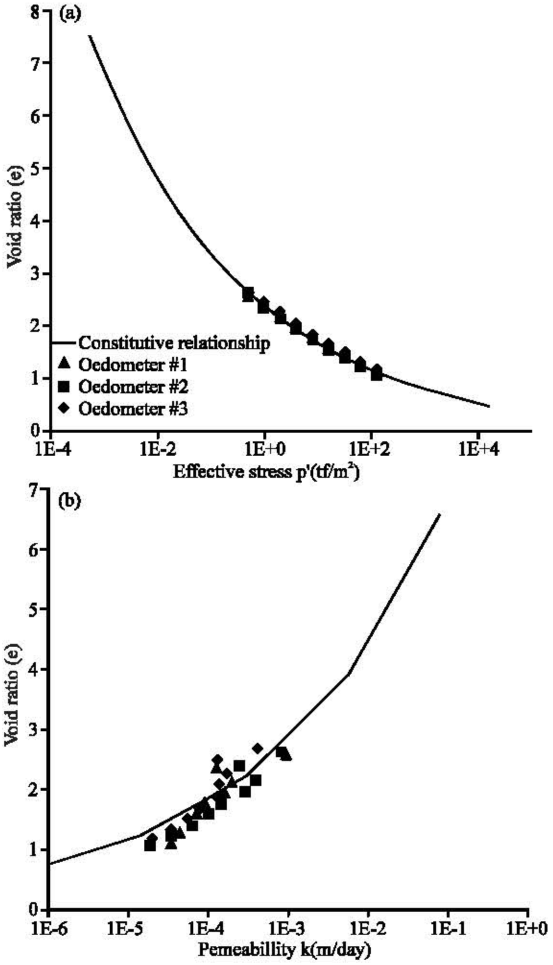

Fig. 6: Constitutive relationship (F1 section); a) e-log σ'; e-k

obtained in the void ratio, e = 1.540~4.458 section and as the void ratio decreased, the effective stress increased non-linearly. The permeability coefficient showed increase with a slightly non-linear relationship with increase of void ratio. Also, at void ratio higher than that in the standard consolidation test, the e-log p', e-log k gradient increased.

Void ratio-permeability coefficient-effective stress: For dredging reclamation clay with a high void ratio, it is necessary to perform large deformation analysis of the finite strain consolidation theory which can take into account change of compressibility and permeability according to effective stress. During the analysis such change relies on the relationship between void ratio (e) and effective stress (σ') and that between void ratio (e) and permeability coefficient (k) which are referred to as constitutive relationship in finite strain consolidation (Schiffman *et al*., 1984). For the purpose of fully reflecting the non-linearity of the void ratio-effective stress and void ratio-permeability coefficient relationships in consolidation prediction, different forms of relationship equations based on function have been proposed (Koppula and Morgenstern, 1982; Somogyi, 1979; Carrier and Bromwell, 1984; Schiffman *et al*., 1985; Yano, 1985; Gibson *et al*., 1981). In particular, many of the expressions are in the form of exponential function or power function. In this study, based on self-weight consolidation and consolidation (standard consolidation test, CRS) tests for dredging clay with high void ratios, we identified the relationship between void ratio and effective stress and that between void ratio-permeability coefficient and applied the power function equation proposed by Somogyi (1979, 1980).

$$e = A\sigma'^{B} \tag{2}$$

$$k = Ce^{D} \tag{3}$$

Where A, B, C, D: each coefficient of the constitutive equation.

Computation of constitutive equation: Due to difficulty with directly obtaining the constitutive relationship of high void ratios, a method for calculating self-weight consolidation and then inverse method it has been proposed (Milkasa, 1965; Yamagami *et al*., 2000). Through standard consolidation test and CRS consolidation test, we obtained the void ratio-effective stress and void ratio-permeability coefficient relationships of the low void ratio section.

With the result of standard consolidation test as a reference point, we estimated a constitutive equation in the form of power function as proposed by Somogyi (1980) and then compared it with the result of time-settlement of surface height obtained from the self-weight consolidation test based on centrifugal model test. In the end, the constitutive relationship that simulates the results of the test and finite strain consolidation analysis most suitably is selected. In this study, we inverse method the self-weight consolidation test result using samples from six dredging reclamation sites in order to compute the constitutive equation. The constitutive relationship between void ratio-effective stress and void ratio-permeability coefficient in F1 sample was calculated by modifying the constitutive equation based on the reference point obtained in the laboratory test. F1 Then, we calculated the constitutive equation of e-$^{\sigma'}$, e-k which most-accurately predicts the results of the finite strain consolidation analysis using predicted constitutive relationship and self-weight consolidation based on the centrifugal model test and presented the constitutive equation in Fig. 7 and 8.

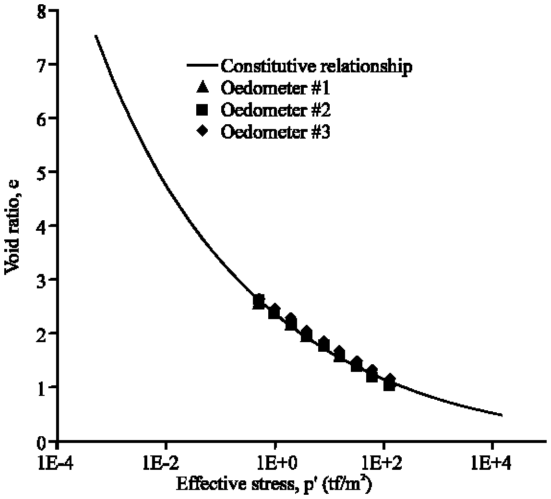

Fig. 7: Comparison of centrifuge test results with numerical analysis (F1 section)

Table 3: Constitutive relationship equation

Section	Void ratio-effective stress(kPa)	Void ratio-permeability(m/day)
F1	$e = 2.35\sigma'^{-0.154}$	$k = 4.43\times10^{-6}\ e^{5.21}$
F2	$e = 1.73\sigma'^{-0.121}$	$k = 1.38\times10^{-5}\ e^{5.01}$
F3	$e = 1.82\sigma'^{-0.154}$	$k = 1.30\times10^{-5}\ e^{4.90}$
F4	$e = 1.92\sigma'^{-0.167}$	$k = 7.00\times10^{-6}\ e^{5.30}$
F5	$e = 2.01\sigma'^{-0.132}$	$k = 3.46\times10^{-5}\ e^{4.54}$
F6	$e = 2.15\sigma'^{-0.118}$	$k = 1.34\times10^{-5}\ e^{4.18}$

Regarding the constitutive relationship of sample collected from the Busan dredging reclamation site (F1) in the void ratio-effective stress relationship equation coefficient A was 2.35 and B-0.154 and in the void ratio-permeability coefficient relational equation, C was 7.11×10^{-6} and D 4.70. Table 3 shows the constitutive equation results of dredging clay in the Busan Region.

Dredging clay collected in six dredging reclamation sites in Busan were analyzed and the relevant six constitutive equations were linearly analyzed based on a log-log scale. The results were shown in diagrams, Fig. 9 and subsequently, the representative constitutive equations were computed. As the constitutive relationship was analyzed based on the power function relational equation proposed by Somogyi (1979) it has a straight-line relationship on the log-log scale. Based on the linear relationship, we computed the arithmetic mean and then the representative constitutive Eq. 4 and 5:

$$e=2.18\sigma'^{-0.142} \quad (4)$$

$$k=1.62\times10^{-5}e^{4}.82 \quad (5)$$

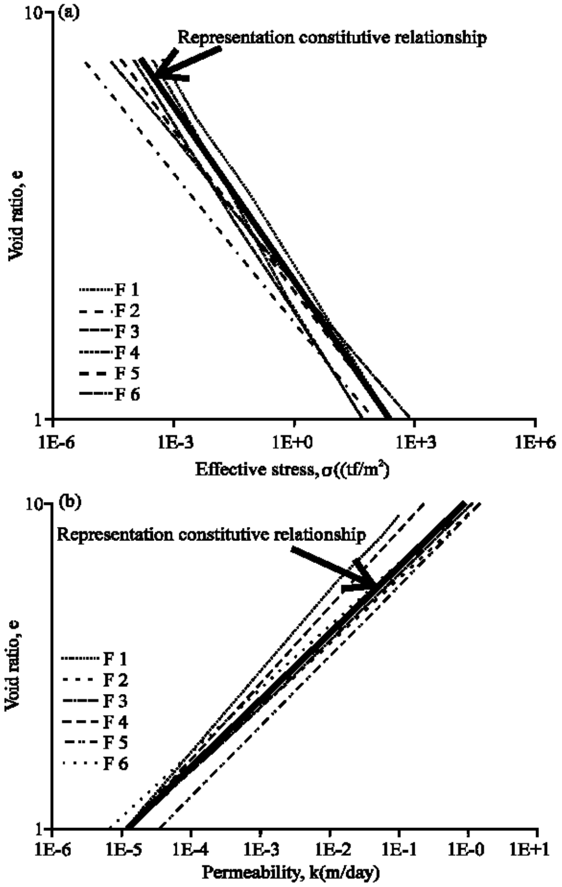

Fig. 8: Logarithmic constitutive relationship; a) e-σ′; b) e-k

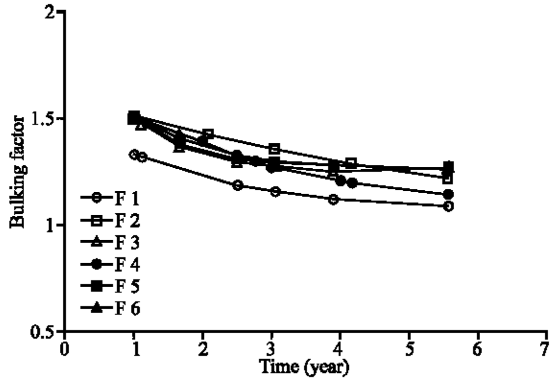

Fig. 9: Bulking factor with time

RESULTS AND DISCUSSION

Computation of bulking factor: To estimate the bulking factor with time, amount of dredging and eventual consolidation settlement when burying a set amount of dredging materials in a land of a specific size through a

Table 4: Input data

Section	Moisture content of soil (%)	Specific weight of spoil (Gs)	Void ratio of natural ground (e)	Original height of soil (m)	Reclamated height (m)	Dumping speed (cm/day)	Dumping period (Month)
F1	75.0	2.71	2.03	DL-2.5	DL+6.9	0.303	12
F2	60.3	2.71	1.63	DL-2.5	DL+6.9	0.327	12
F3	62.5	2.71	1.67	DL-2.5	DL+6.9	0.930	12
F4	83.3	2.71	2.25	DL-7.9	DL+8.5	1.620	24
F5	60.0	2.71	1.62	DL-4.5	DL+7.0	0.312	12
F6	63.9	2.71	1.73	DL+5.7	DL+7.0	0.213	3

Table 5: Analysis result

Section	Initial bulking factor	Self-weight consolidation after the end of bulking factor
F1	1.325	1.083
F2	1.492	1.246
F3	1.499	1.214
F4	1.383	1.134
F5	1.508	1.266
F6	1.516	1.250

pump, we conducted a numerical analysis according to the finite strain consolidation theory. For the analysis we used PSDDF (Primary consolidation, Secondary compression and Desiccation of Dredged Fill) developed by US Army Corp of Engineers as it can simulate step-by-step dumping and take into account non-linear void ratio-effective stress-permeability coefficient, etc. The input and analysis factors for each site are presented in Table 4.

For the void ratio of natural ground, the bulking factor can be computed based on soil surveying of the site. Bulking factor is defined by Eq. 6. The sites F1, F2, and F3 were assumed to have been filled over 12 months while F4-F6 were analyzed based on the actual site conditions. The bulking factor at the time of reclamation completion was estimated to range between 1.325 and 1.516 and from 36 months after the completion, converged to 1.083-1.266. Figure 9 and Table 5 present the result of the numerical analysis.

$$B.F = \frac{1+e_i}{1+e_0} \quad (6)$$

CONCLUSION

This study conducted a series of consolidation tests and centrifugal model tests for spoil collected in the Busan region and identified the relevant consolidation characteristics and constitutive equations related to the void ratio-effective stress-permeability coefficient. And then a finite deformation consolidation analysis was conducted in order to investigate the status of the dredging reclaimed land. The results of this study were as follows.

The basic properties test result showed: the specific weight ranged between 2.707 and 2.719 with the average of 2.713. The average liquid limit was 54.46%, average plastic limit 19.27% and average plasticity index 35.20. The percentage passing the #200 sieve was over 97.61% and the clay particle content was between 21.23 and 28.87%. The clay activity was on average, 1.43, ranging between 1.0 and 1.8 which is relatively high.

The consolidation test result showed, the compression index of Busan dredging clay ranged between 0.427 and 0.642 and permeability change index between 0.850 and 1.014.

The representative constitutive equation of Busan dredging clay showed: in the void ratio-effective stress relationship equation, coefficient A was 2.18 and B-0.142 and in the void ratio-permeability coefficient relationship equation, coefficient C was 1.62×10^{-5} and D 4.82.

The numerical analysis result showed at the time of reclamation completion, the bulking factor ranged between 1.496 and 1.550 and after 36 months, converged to 1.190-1.250.

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