

Design charts for estimating the consolidation times of reclaimed marine clays in Korea

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Abstract. To predict the consolidation behavior of dredged and reclaimed marine clays exhibiting consolidation settlement with large strains, the finite strain consolidation theory must be used. However, challenges in appropriately applying the theory and determining input parameters make design and analysis studies difficult. To address these challenges, design charts for predicting the consolidation settlement of reclaimed marine clays are developed by a numerical approach based on the finite strain consolidation theory. To prepare the design charts, a sensitivity analysis of parameters is performed, and influencing parameters, such as initial void ratio and initial height, as well as the non-linear constitutive void ratio-effective stress-permeability relation, are confirmed. Six representative Korean marine clays obtained from different locations with different liquid limits are used. The design charts for estimating the consolidation times corresponding to various degrees of consolidation are proposed for each of the six representative clays. The consolidation settlements predicted from the design charts are compared to those in previous studies and at an actual construction site and are found to agree well with them. The proposed design charts can therefore be used to solve problems related to the consolidation of reclaimed marine clays having large strains.

Keywords: consolidation settlement; design chart; finite strain consolidation theory; marine clay; non-linear constitutive relationship

1. Introduction

Predicting the consolidation settlement of reclaimed sites dredged by marine clay is very important because marine clay exhibits large strains. The large settlement can be predicted empirically based on settling column tests, but this approach is not appropriate for reflecting various consolidation conditions. Therefore, a finite strain consolidation theory was developed to overcome limitations of the classical Terzaghi's consolidation theory for small strain deformation by Mikasa (1965) and Gibson *et al.* (1967). The theory is appropriate to analyze the large deformations of clays. In the finite strain consolidation theory, the consolidation behavior of clays is governed by a non-linear void ratio-effective stress-permeability relationship. The constitutive relationship was proposed as a power function equation by Somogyi (1979) and Somogyi *et al.* (1984). Carrier *et al.* (1983) found a correlation between the constitutive relationship of the power function

and physical properties, such as liquid limits, plastic limits, and plastic activity. Gibson *et al.* (1981) developed a simple governing equation based on the finite strain consolidation theory using the constitutive relationship of the void ratio and effective stress, which they assumed as an exponential function. Pane (1981) proposed a numerical approach by using the explicit finite difference. Lee *et al.* (1988) determined a numerical solution using the constitutive relationship of the exponential function.

The finite strain consolidation theory that is appropriate for large deformation clay is typically applied in numerical analyses as it assumes that an analytical solution does not exist. Numerical analysis conducted using the equation that is governed by the finite strain consolidation theory is known to estimate a large consolidation settlement (Stark *et al.* 2005a, b, Liu and Griffiths 2015, Xie *et al.* 2016, Hu *et al.* 2018, Liu *et al.* 2019). However, such a numerical analysis is difficult to use in practice because it requires a firm understanding of the theory and several laboratory tests. In particular, making predictions in the preliminary design stage is difficult. To overcome this limitation, studies that propose solution charts have been performed. Fox (1999) proposed a solution chart using a piecewise linear approach proposed by McVay *et al.* (1989). Morris (2002) proposed a solution chart using the finite strain consolidation theory. Brandenburg (2017) proposed an implicit finite difference code, and deployed through an HTML user interface. However, a solution that can be easily applied to Korean marine clay has yet to be determined. In

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Table 1 Applied values for parametric sensitivity analysis

Type	Parameters	Symbol	Ranges	Default values
Physical and consol. properties	Specific gravity of soil solid	G_s	2.60–2.80	2.70
	Unit weight of water (kN/m ³)	γ_w	9.81–10.2	10.01
	$e = A\sigma'^B$ (σ' : kPa)	A	1.0–5.0	3.0
		B	-0.3 to -0.1	-0.2
	$k = Ce^D$ (k: m/day)	C	$(0.001-1) \times 10^{-3}$	5×10^{-5}
D		3.0–8.0	5.5	
Conditions of reclamation	Initial void ratio	e_0	2.0–30.0	16.0
	Reclaimed initial height (m)	h_0	2.0–30.0	16.0
	Overburden pressure (kPa)	Q	0–200	0

this paper, we propose a design chart for consolidation times corresponding to degrees of consolidation that, together with design charts for final consolidation settlement developed in a previous study (Jun and Kwon 2020, Jun *et al.* 2021), can be used to predict the consolidation time of Korean marine clay.

2. Sensitivity analysis of the parameters influencing the consolidation time

To prepare a design chart for the consolidation time of marine clay, a sensitivity analysis of specific parameters was performed. The parameters of marine clay are physical and consolidation properties such as void ratio-effective stress-permeability and construction conditions as initial void ratio, initial height. Table 1 shows the default values and ranges for the parameters utilized in the parametric analysis. The values and ranges were obtained by back analyses and laboratory tests performed on clay samples from dredged-reclaimed construction sites (Jun and Kwon 2020).

For the parametric study, consolidation time was defined as the period required to reach a consolidation degree of 80% or 95%. The consolidation time (t_{80}) needed to reach a consolidation degree of 80% was 4.42 days, and the consolidation time (t_{95}) needed to reach a consolidation degree of 95% was 30.57 days. The sensitivity analysis of the parameters for the consolidation time revealed that, as shown in Fig. 1, the consolidation time changes linearly with the specific gravity of solid and unit weight of water. The correlation between consolidation time and the initial void ratio and initial height is linear on semi-logarithmic scale. The consolidation time changed linearly with coefficients C and D on a logarithmic scale. C and D are coefficients of the constitutive relationship equation for the void ratio (e) and permeability (k), $k = Ce^D$. The parameters A, C, D, e_0 , and H_0 affect the consolidation time significantly, but the specific gravity of solid (G_s) and unit weight of water (γ_w) affect the consolidation time slightly. Therefore, for the design chart, parameters A, C, D, e_0 , and H_0 , and the applied representative values of G_s and γ_w were considered.

3. Design charts for estimating consolidation time

3.1 Design charts for consolidation time

The consolidation settlement according to time should be required to design or maintenance a dumping area in practice. The surface elevation, average void ratio, and volume of reclaimed clay can be predicted by the consolidation settlement according to time. In the study, a design chart for consolidation time was proposed at various degrees of consolidation. The consolidation settlement at a specific time can be calculated by multiplying the final settlement and the degree of consolidation. The degree of consolidation is the average value of the reclaimed clay layer. To estimate the final settlement, we used our previous research findings (Jun *et al.* 2021).

The major parameters influencing the consolidation time are the initial void ratio, initial height, and constitutive void ratio-effective stress-permeability relationship determined through parametric analysis. Therefore, we prepared design charts to predict the consolidation times of six representative Korean clays. The properties of the six representative clays listed in Table 2 were obtained by conducting basic physical property tests, consolidation tests, centrifugal experiments, and a back analysis based on the finite strain consolidation theory using marine clay samples from a dredged-reclaimed construction site in Korea. Fig. 2 shows the physical and consolidation properties of the six representative clays.

Design charts for consolidation time are proposed to estimate the degrees of consolidation (98%, 95%, 90%, 85%, 80%, 70%, 60% and 50%) for six representative marine clays. The consolidation time can be found by using the initial void ratio and initial height on the design charts, as shown in Figs. A1–A6 in Appendix A. Fig. A1 shows the design charts for Busan L marine clay for eight degrees of consolidation. Fig. A2 is the design chart for Busan H marine clay. Figs. A3 and A4 are the design charts for Gwangyang marine clays. Figs. A5 and A6 are the design charts for Incheon marine clays. These design charts consist of numerical solutions without any conversion. Therefore, the design charts can be analyzed directly to predict the consolidation times and suffer only from a reading error under the finite strain consolidation theory.

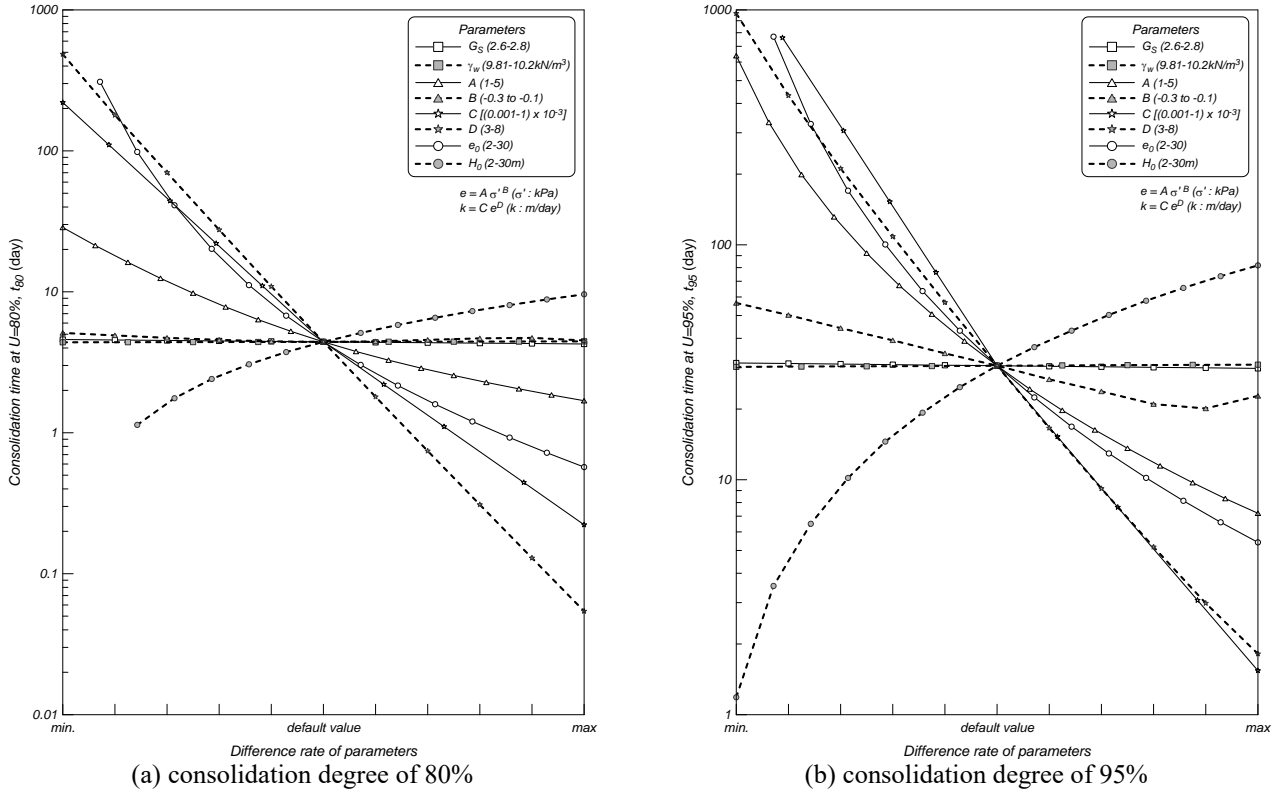


Fig. 1 Parametric sensitivity analysis for the consolidation time

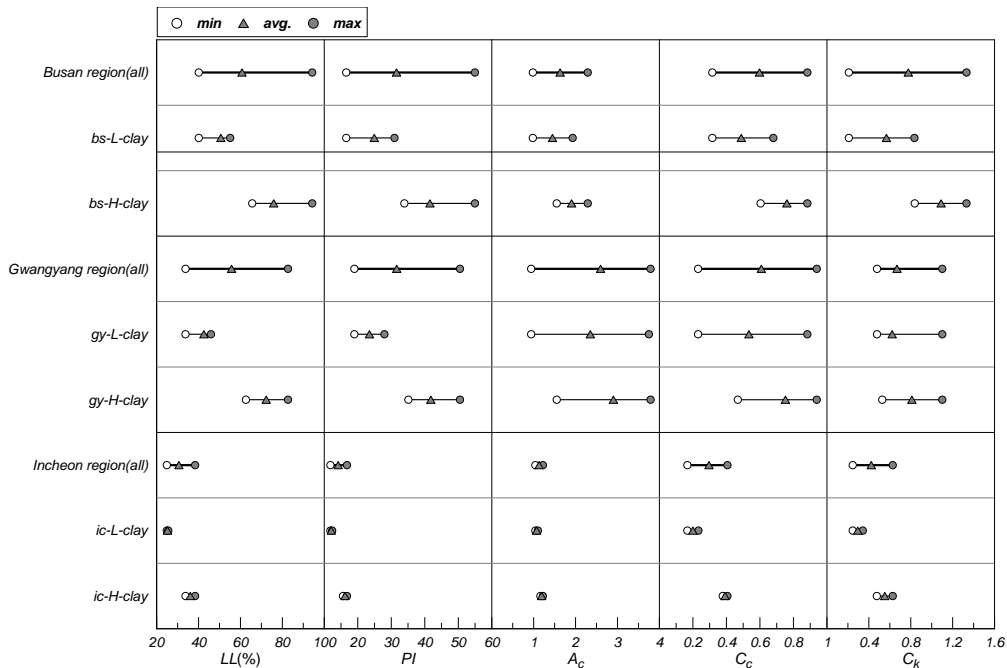


Fig. 2 Physical and consolidation properties of six representative clays

3.2 Flowchart used in practice

Fig. 3 is a flowchart of the process followed to prepare the design charts in practice. To estimate the consolidation settlement of dredged-reclaimed clay, the initial void ratio and initial height should be known. Thereafter, the final

consolidation settlement and consolidation time as a degree of consolidation are sequentially estimated. The final settlement proposed by a previous study (Jun *et al.* 2021) can be used to prepare regional design charts or a general design chart based on information about the constitutive void ratio-effective stress-permeability relationship. After

Table 2 Representative constitutive relationship equation

Region	Symbol	Representative constitutive relationship		Applicable range of liquid limits
		Void ratio-effective stress(kPa)	Void ratio-permeability(m/day)	
Busan	bs-L-clay	$e = 3.1 \sigma'^{-0.19}$	$k = 9 \times 10^{-6} e^{5.5}$	40–60%
	bs-H-clay	$e = 4.3 \sigma'^{-0.20}$	$k = 6 \times 10^{-6} e^{4.5}$	60–80%
Gwangyang	gy-L-clay	$e = 2.9 \sigma'^{-0.18}$	$k = 9 \times 10^{-6} e^{6.0}$	40–60%
	gy-H-clay	$e = 3.9 \sigma'^{-0.20}$	$k = 8 \times 10^{-6} e^{4.5}$	60–80%
Incheon	ic-L-clay	$e = 1.7 \sigma'^{-0.15}$	$k = 1 \times 10^{-4} e^{5.5}$	20–30%
	ic-H-clay	$e = 2.2 \sigma'^{-0.17}$	$k = 5 \times 10^{-5} e^{5.5}$	30–40%

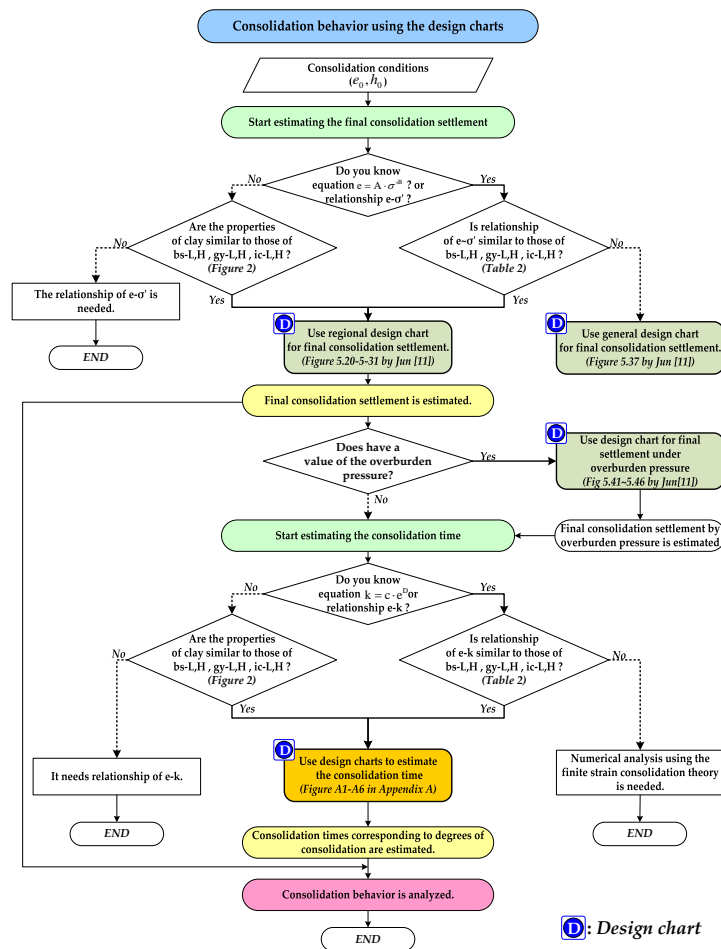


Fig. 3 Flowchart showing the method used to estimate consolidation settlement and time with the design charts

estimating the final consolidation settlement, consolidation settlements according to time can be calculated at degrees of consolidation as 98%, 95%, 90%, 85%, 80%, 70%, 60% and 50%.

4. Application of the design chart

4.1 Comparison with previous laboratory studies

Kim (2006) investigated the consolidation settlements of Korean dredged-reclaimed marine clay by a column test and

a centrifugal experiment. The properties of sample A were similar to those of Busan H marine clay, and those of sample B were similar to those of Gwangyang H marine clay. The final consolidation settlement was calculated by the general design chart in Jun *et al.* (2021), and the values for sample A and sample B were 3.99 m and 3.79 m, respectively, as shown in Table 3.

The consolidation times of sample A were estimated from the design chart of Busan H marine clay, and those of sample B were estimated from the design chart of Gwangyang H marine clay, as shown in Table 4 and Fig. 4. The consolidation settlements obtained by Kim (2006) were

Table 3 Properties, initial conditions, and final consolidation settlement of Kim (2006)’s study

Sample	LL (%)	Properties and result by Kim (2006)				Design chart *s _f (m)
		Constitutive relationship		e ₀	H ₀ (m)	
A	47.2	$e = 6.72\sigma'^{-0.31}$	$k = 6 \times 10^{-6}e^{4.05}$	8.10	8.60	3.99
B	55.9	$e = 6.04\sigma'^{-0.27}$	$k = 6 \times 10^{-6}e^{4.06}$	8.07	7.93	3.79

* s_f was calculated based on information in the general design chart proposed by Jun *et al.* (2021)

Table 4 Consolidation times to be obtained from the design charts for Kim (2006)’s study

Sample	Applied design chart	Consolidation times (days) by design chart							
		U = 98%	U = 95%	U = 90%	U = 85%	U = 80%	U = 70%	U = 60%	U = 50%
A	Busan H	1,870	1,256	835 *	616	485	325	233	178
B	Gwangyang H	1,581	1,020	666	480 **	375	240	176	130

* Value as shown in Fig. 4(a); ** Value as shown in Fig. 4(b)

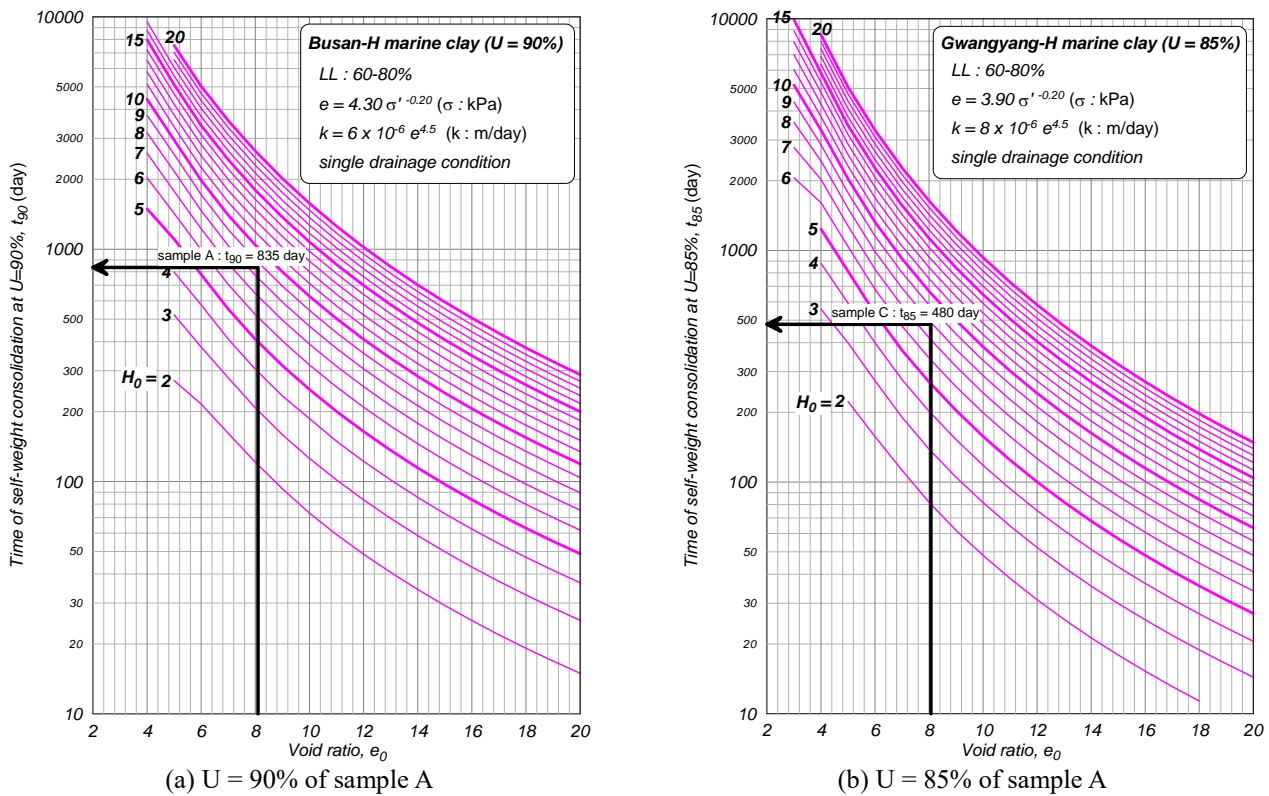


Fig. 4 Estimation of the consolidation times from the design chart

compared with those obtained in this study, as shown in Fig. 5.

Yamagami *et al.* (2000) studied the consolidation settlement for three samples (AC1, AC2, and AC3) that were obtained at the coast of Naruto in the east of Tokushima prefecture in Japan. The values of the properties of the samples fell between those of Busan L marine clay and Gwangyang L marine clay. Therefore, the estimated consolidation times were taken as the averages of the consolidation times of Busan H and Gwangyang L marine clay. The final consolidation settlement was calculated

using the general design chart of a previous work. The consolidation settlement obtained with the design chart is similar to that obtained with the general chart of a previous study, as shown in Fig. 6.

4.2 Application to an actual construction case

The predicted consolidation settlement was compared with that at an actual construction site, Busan landfill construction site. After the site was dredged-reclaimed, it was left undisturbed for a year and experienced a loaded

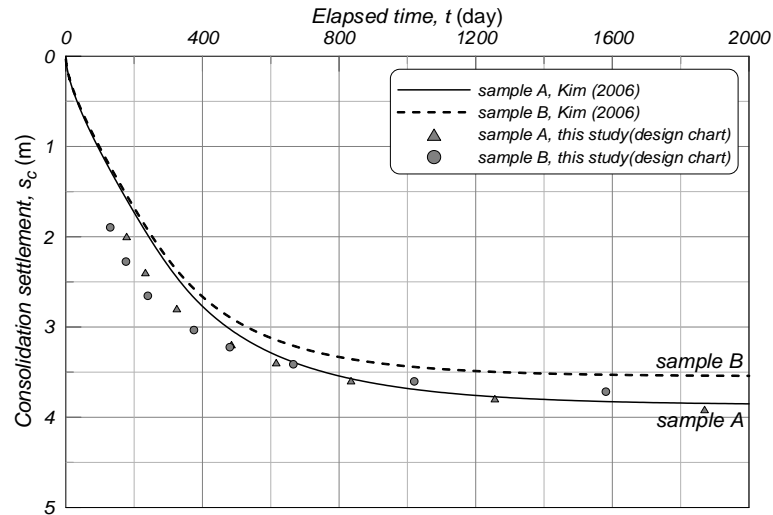


Fig. 5 Comparison of the consolidation times obtained in this study and the study by Kim (2006)

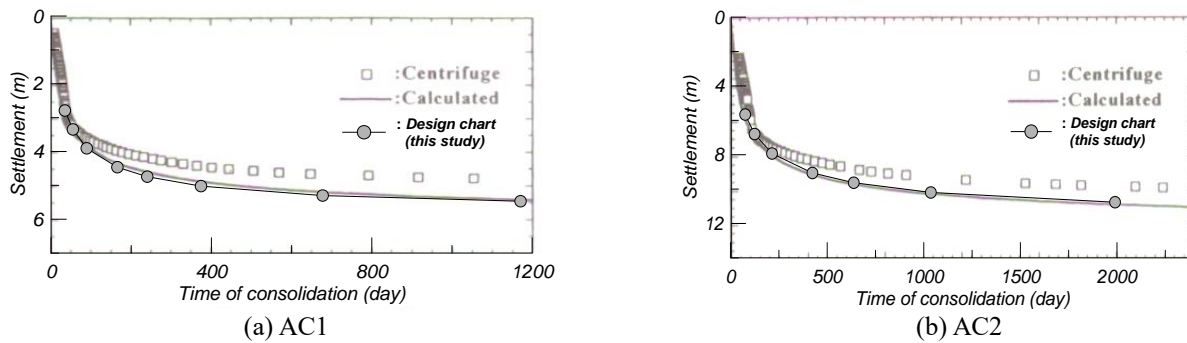


Fig. 6 Comparison of consolidation times between this study and the study by Yamagami *et al.* (2000)

Table 5 Consolidation time and settlement by the design chart (actual design case)

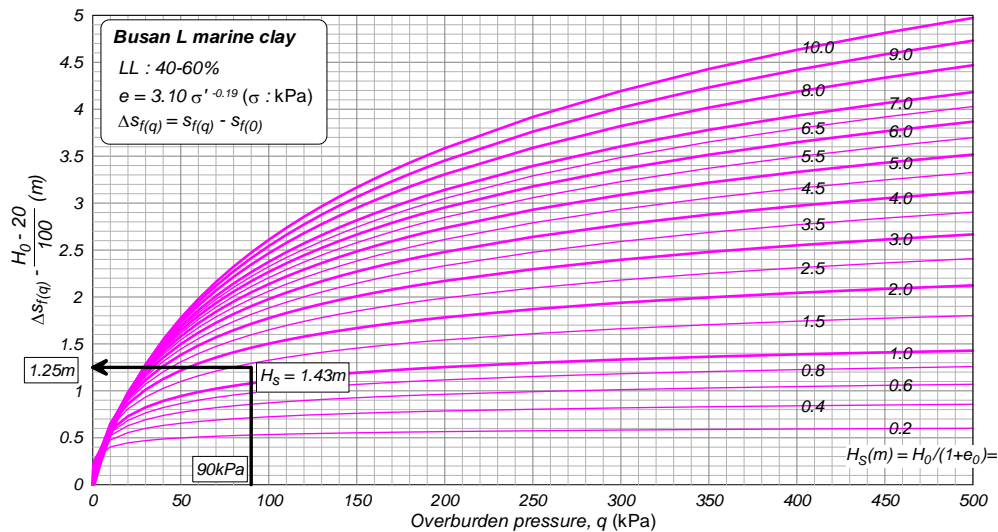
Consolidation	U = 98%	U = 95%	U = 90%	U = 85%	U = 80%	U = 70%	U = 60%	U = 50%
Time (day)	1,288	952	703	563	467	345	263	200
Settlement (m)	3.35	3.25	3.08	2.91	2.74	2.39	2.05	1.71

surcharge of 5 m (90 kPa). The average void ratio of the reclaimed clay was 3.68, and its height was 6.7 m. It had similar properties to Busan L marine clay. The project was designed using the numerical solution of PSSDF (Stark *et al.* 2005a, b).

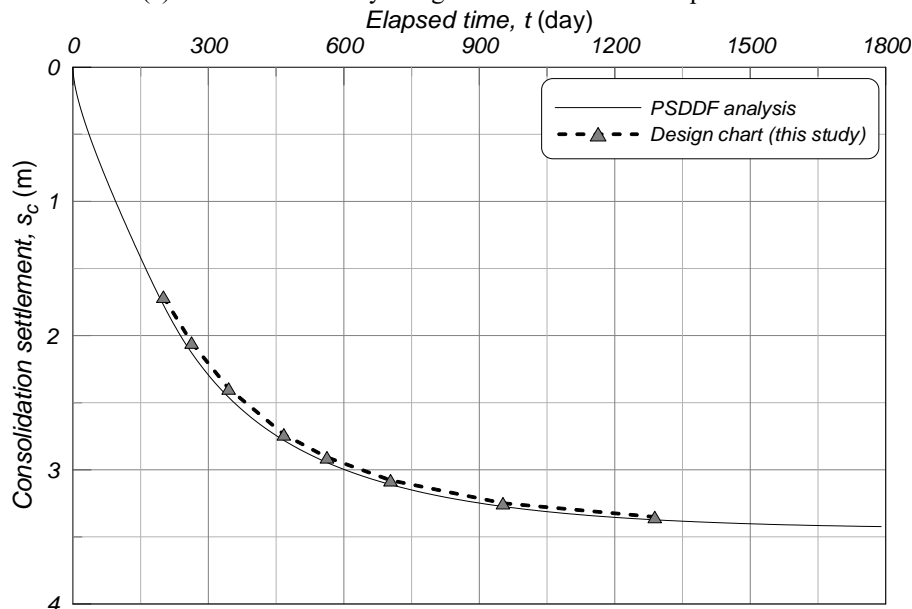
At surcharge load is 90 kPa and $H_s = 6.7 \text{ m} / (1+3.68) = 1.43 \text{ m}$, value of Y-axis in the Fig. 7(a) can be read to 1.25 m. The consolidation settlement by surcharge load, $\Delta S_{f(q)}$ is 1.12 m (= 'value of Y-axis' + $(H_0-20) / 100 = 1.25 + (6.7-20) / 100$). The self-weight consolidation settlement, $S_{f(0)}$ under this condition can be obtained as 2.30 m from design chart of previous study (Jun *et al.* 2021). Final consolidation settlement, $S_{f(q)}$ is 3.42 m (= $S_{f(0)} + \Delta S_{f(q)} = 2.30 + 1.12$). The time at consolidation degrees (98%, 95%, 90%, 85%, 80%, 70%, 60% and 50%) can be read from Fig. A1 (Busan L marine clay case) as Table 5. Fig. 7(b) shows that the consolidation settlements obtained with the project design by PSSDF and in this study by the design chart are similar.

5. Conclusions

In this paper, design charts for consolidation times are proposed to predict the large strain consolidation behavior of dredged-reclaimed marine clay. A sensitivity analysis of the parameters influencing the consolidation time based on the finite strain consolidation theory is performed. The consolidation time has a semi-logarithmic relationship with the initial void ratio and initial height and a logarithmic relationship with coefficients C and D of the constitutive relationship equation for void ratio-permeability. The parameters A, C, D, e_0 , and H_0 influence the consolidation time significantly, whereas the specific gravity of solid and unit weight of water has slight effects. The design charts for estimating consolidation times corresponding to degrees of consolidation 98%, 95%, 90%, 85%, 80%, 70%, 60%, and 50% are proposed for six representative clays in Korea. By using the design charts to estimate the final consolidation settlement and the consolidation time, the settlements



(a) Final settlement by design chart for overburden pressure



(b) Consolidation settlement with elapsed time

Fig. 7 Comparison of the consolidation times obtained in this study and those obtained with the actual design by PSDDF

reached at the given degrees of consolidation could be evaluated. The final consolidation settlement is calculated using the regional design chart or general design chart obtained in our previous study. The agreement between the consolidation times obtained with the proposed design charts and those of previous studies and at an actual construction site confirmed the applicability of the proposed design charts. An evaluation based on the scenario encountered in practice is demonstrated to be able to approach by the design charts. These findings reveal that the proposed design charts can be applied to solve problems related to the consolidation of reclaimed marine clays having large strains. The design chart in this study is considered just primary consolidation except secondary consolidation or creep. If secondary consolidation or creep is significant problem, the design chart couldn't suggest correct settlement according to time.

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Appendix A

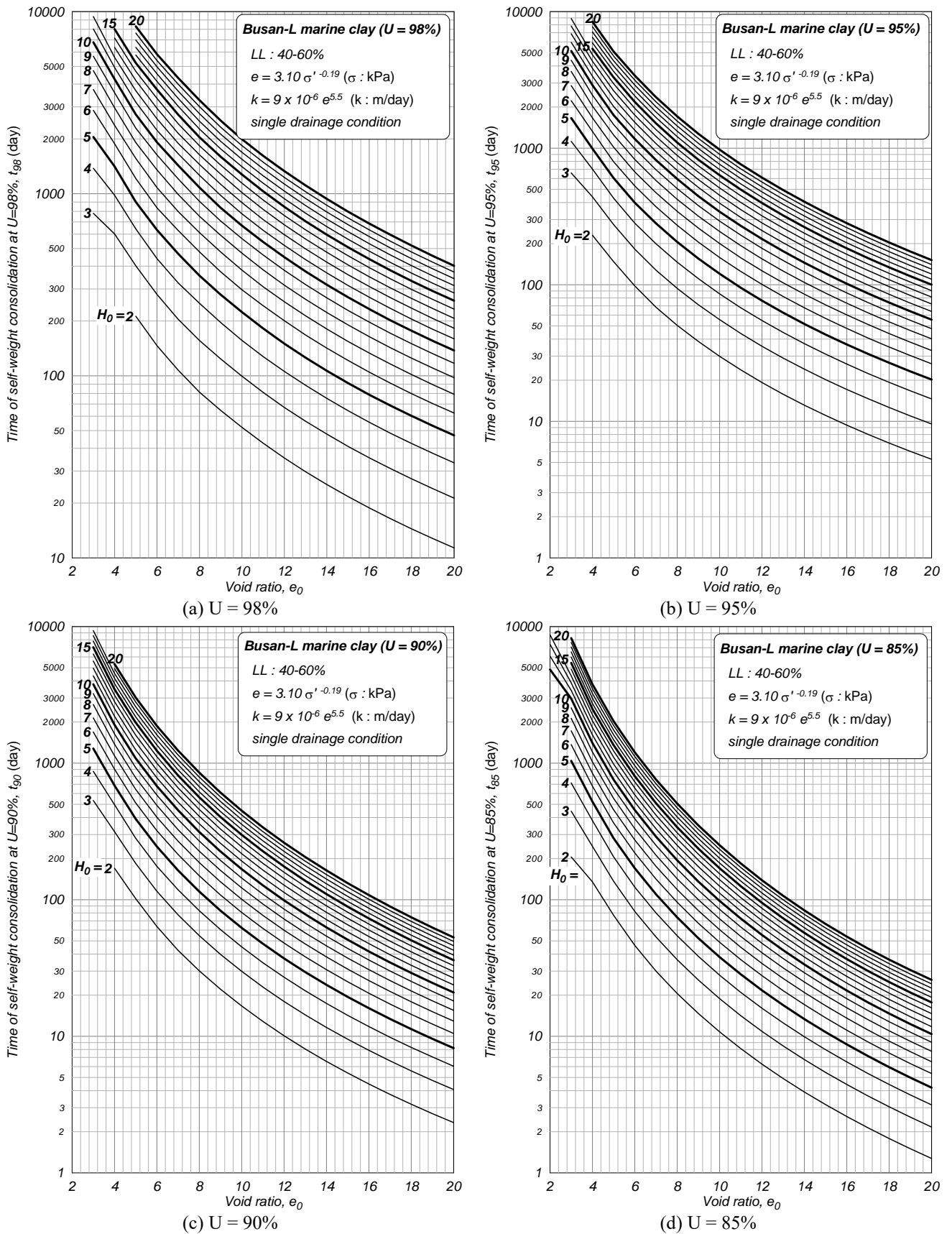
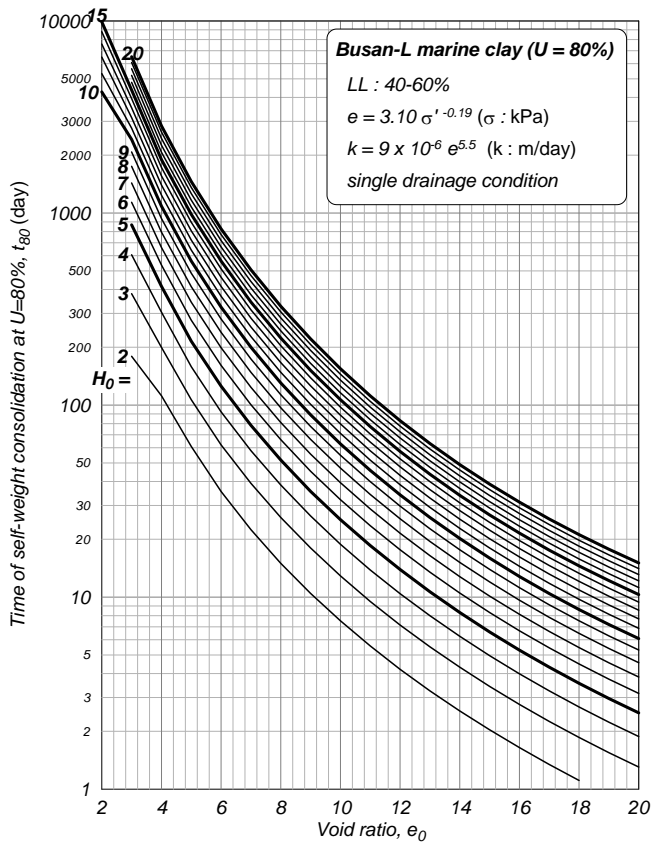
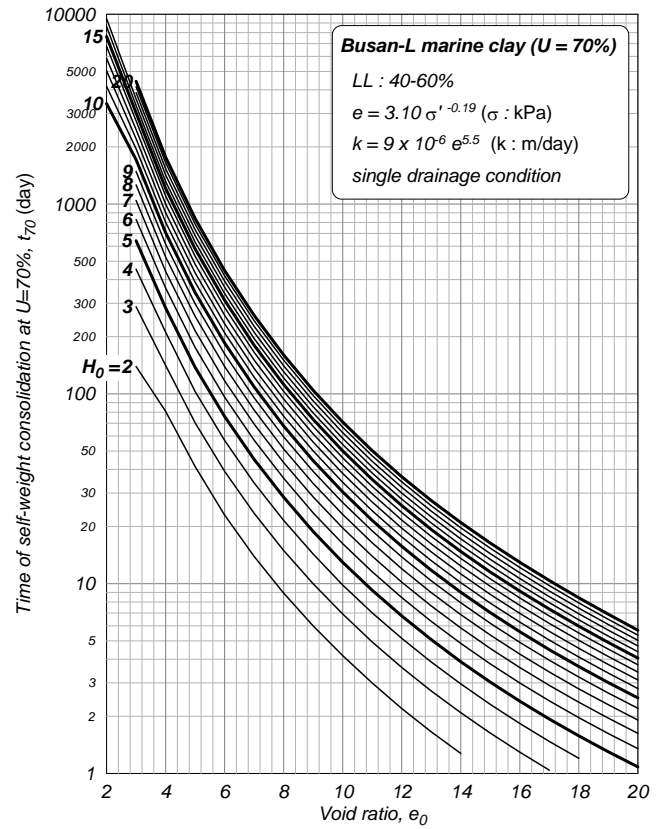


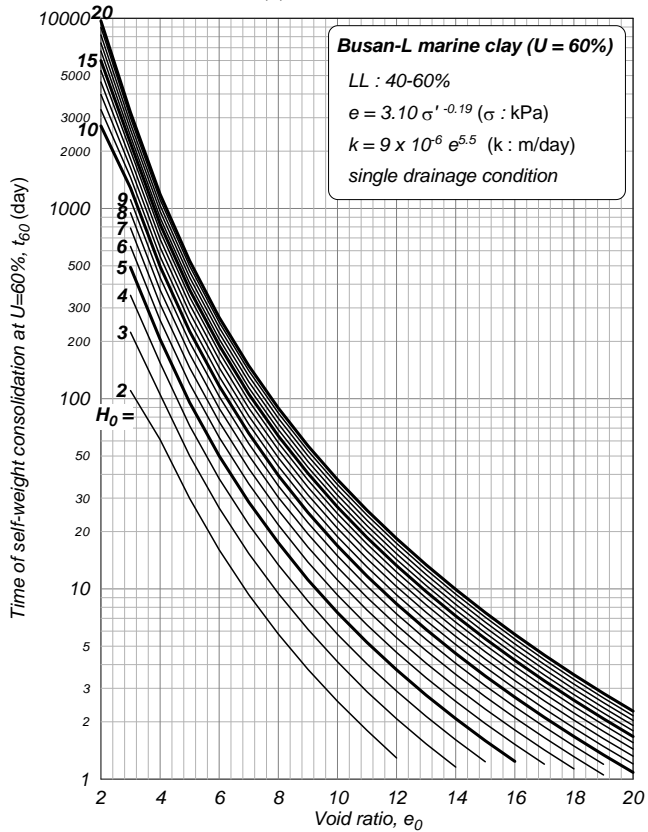
Fig. A1 Design chart of the consolidation time for Busan L marine clay (continue)



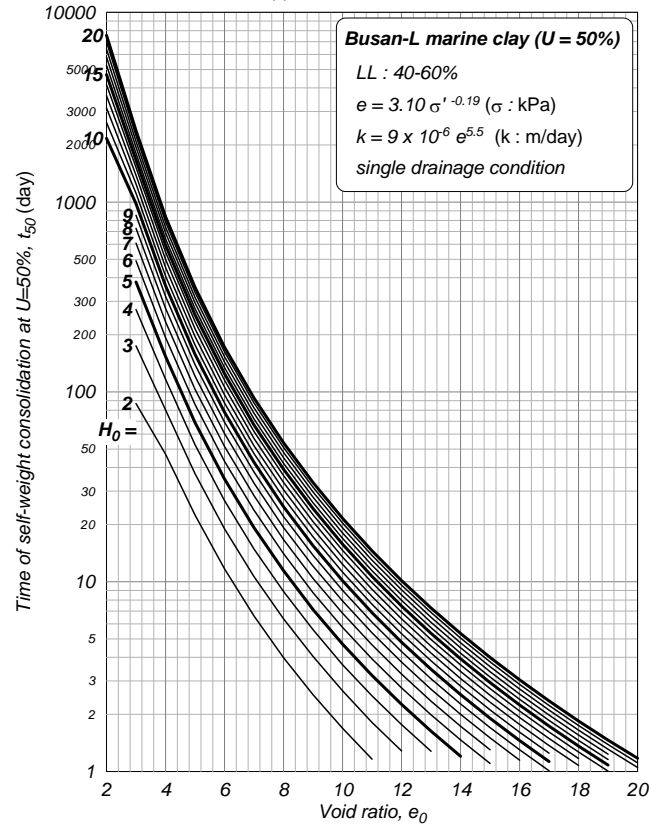
(e) U = 80%



(f) U = 70%

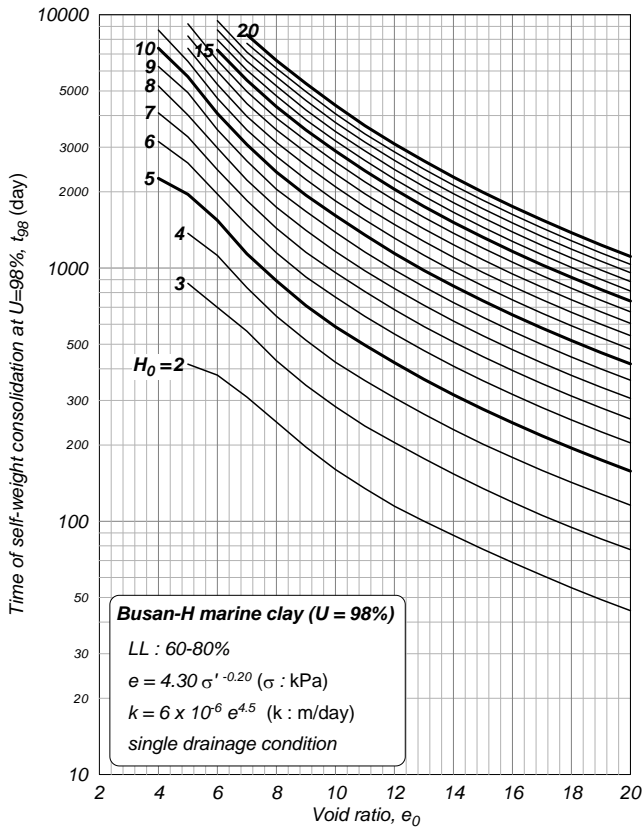


(g) U = 60%

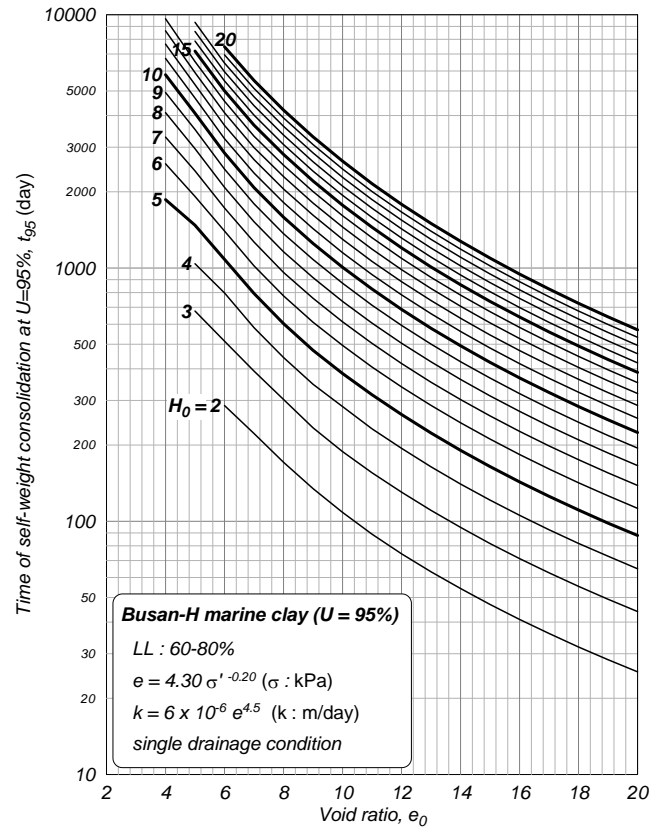


(h) U = 50%

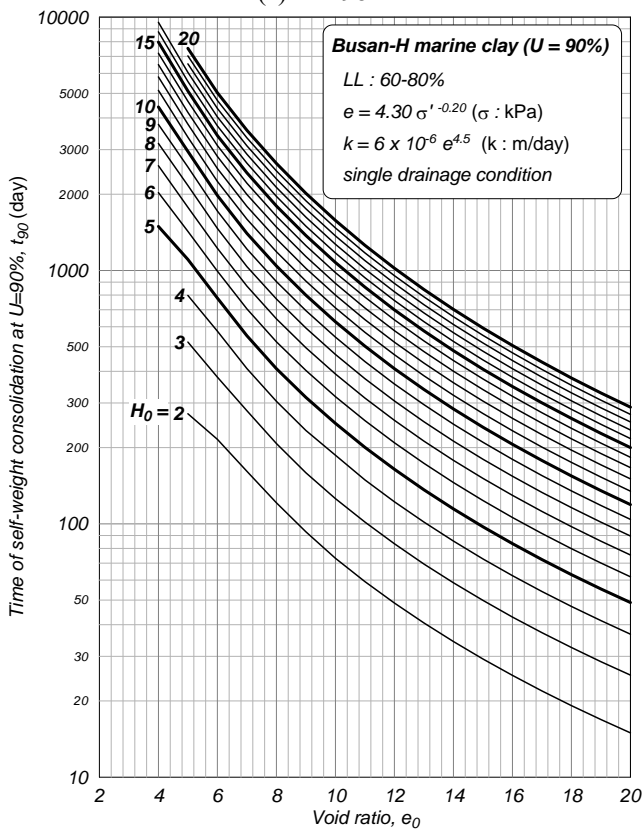
Fig. A1 Design chart of the consolidation time for Busan L marine clay



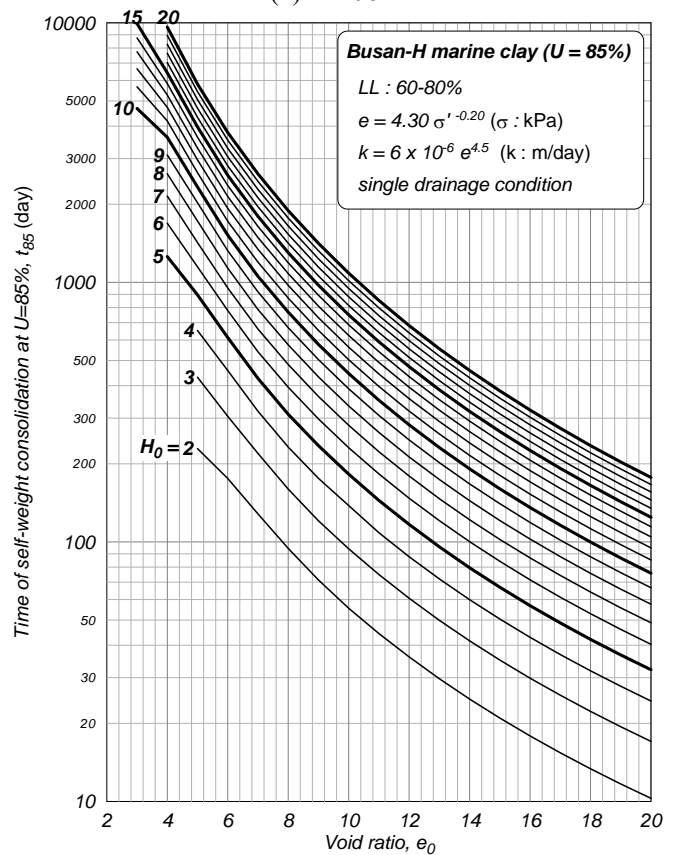
(a) U = 98%



(b) U = 95%

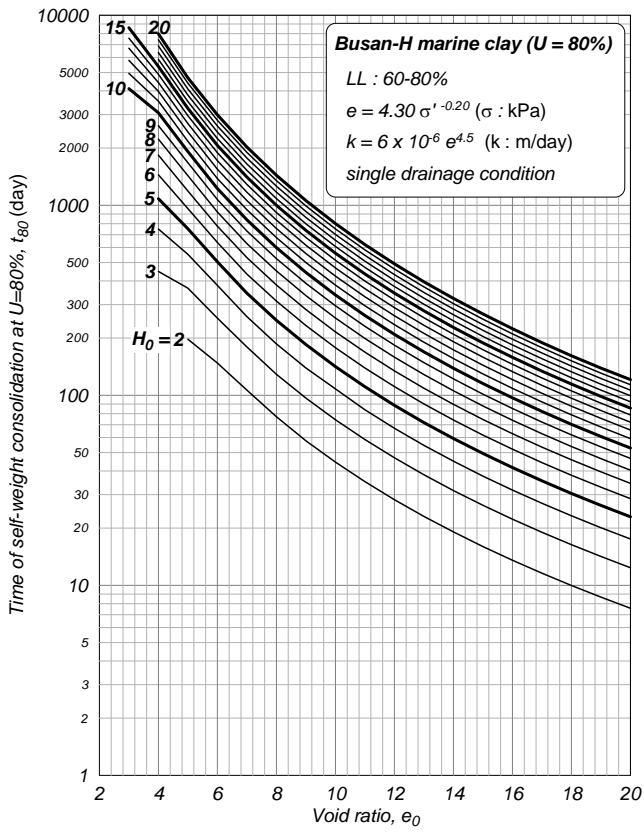


(c) U = 90%

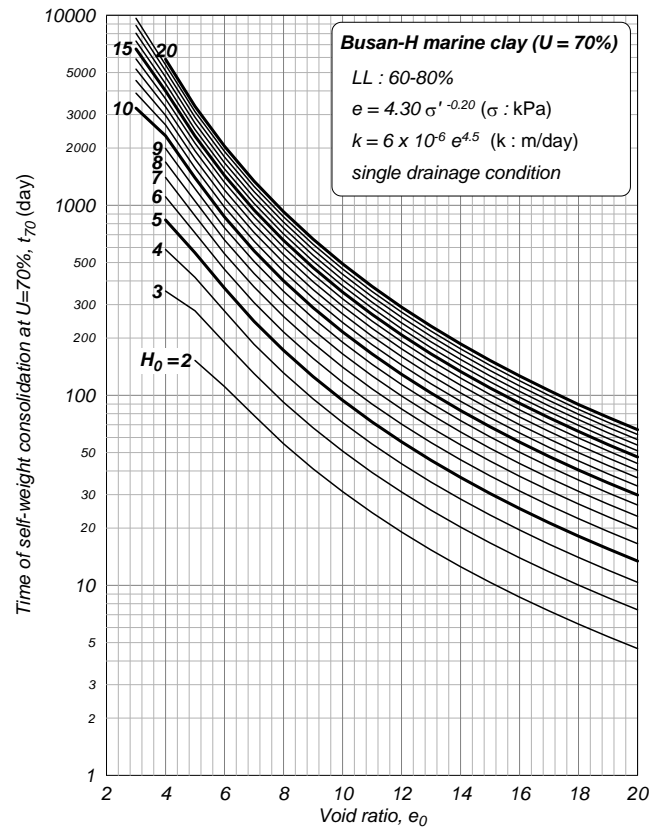


(d) U = 85%

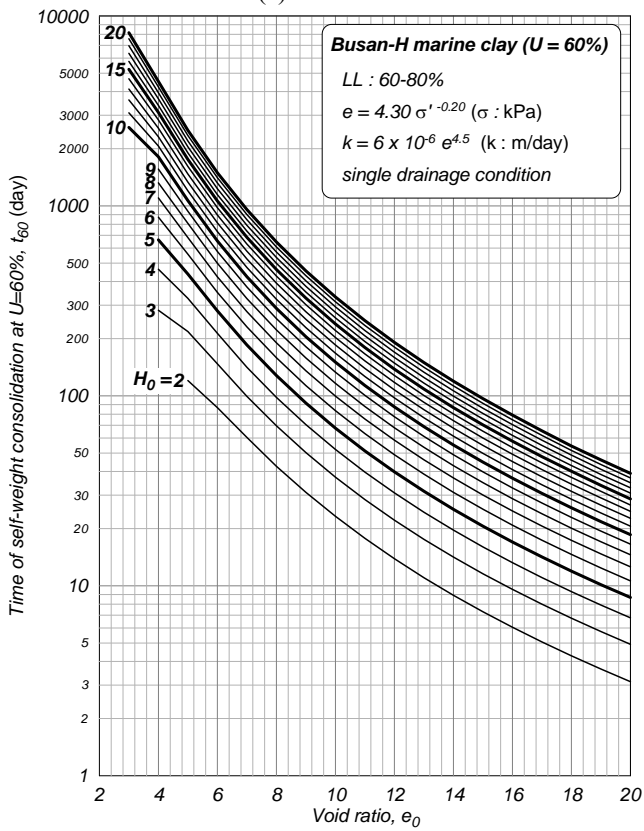
Fig. A2 Design chart of the consolidation time for Busan H marine clay (continue)



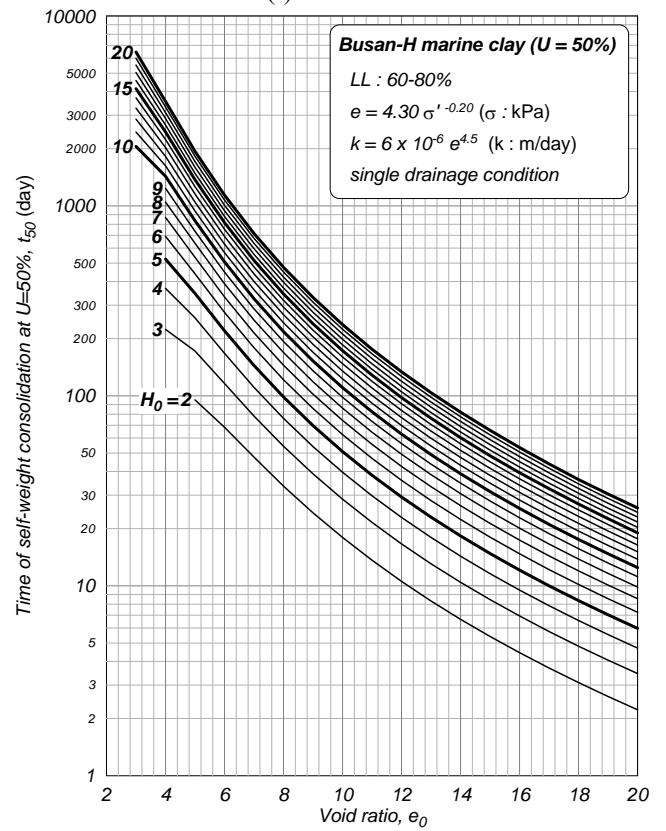
(e) U = 80%



(f) U = 70%

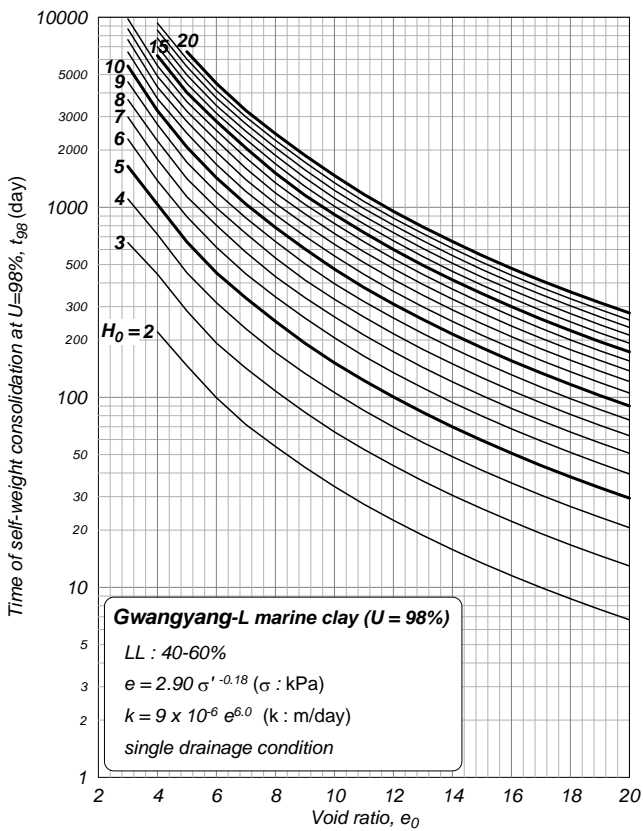


(g) U = 60%

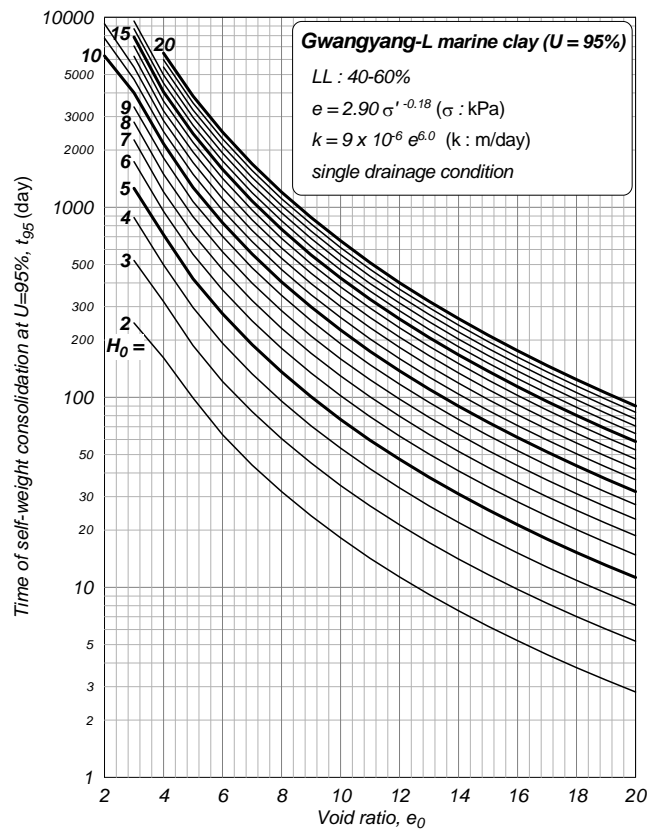


(h) U = 50%

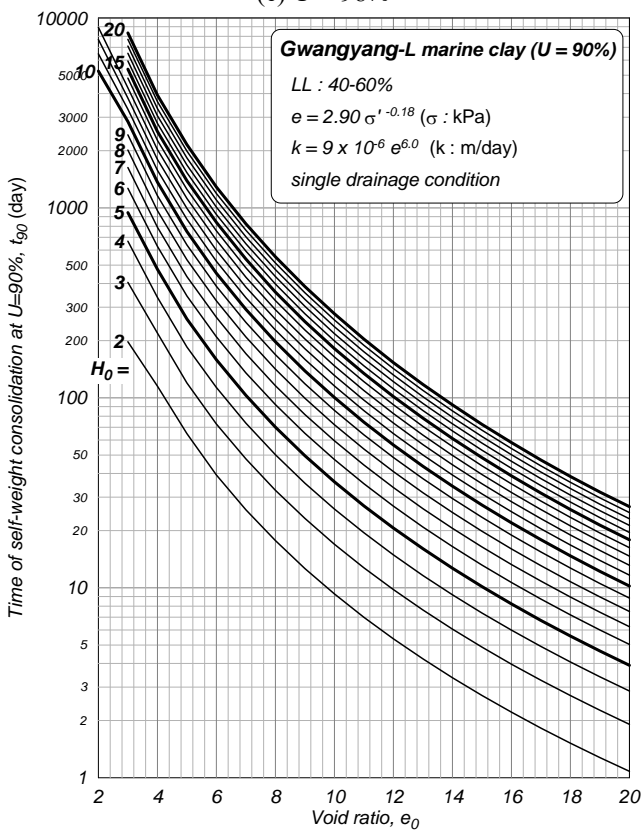
Fig. A2 Design chart of the consolidation time for Busan H marine clay



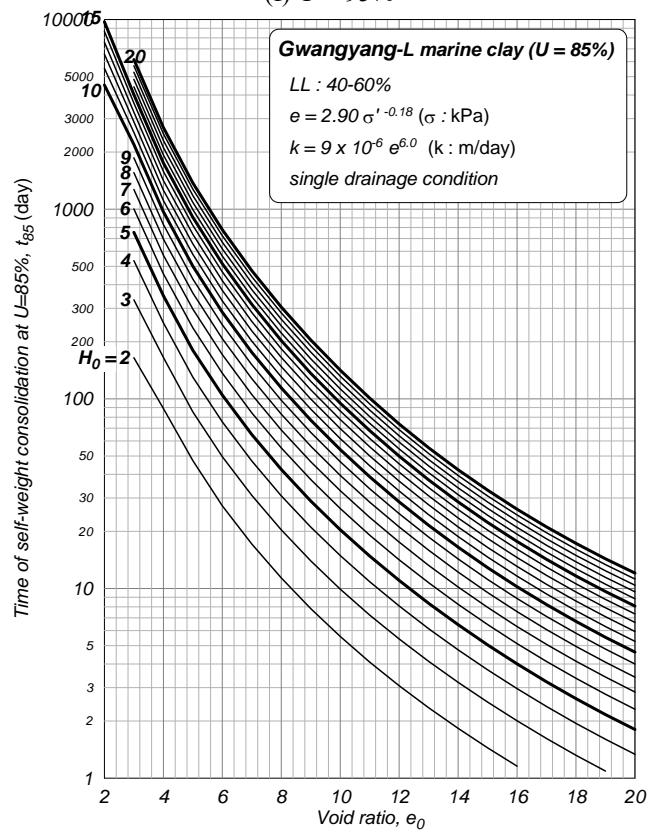
(e) U = 98%



(f) U = 95%



(g) U = 90%



(h) U = 85%

Fig. A3 Design chart of the consolidation time for Gwangyang L marine clay (continue)zh

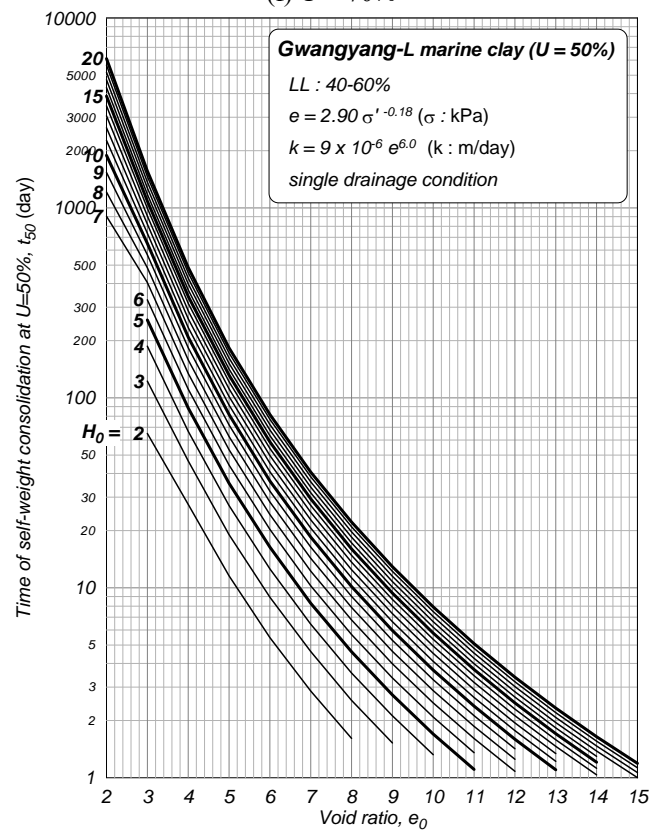
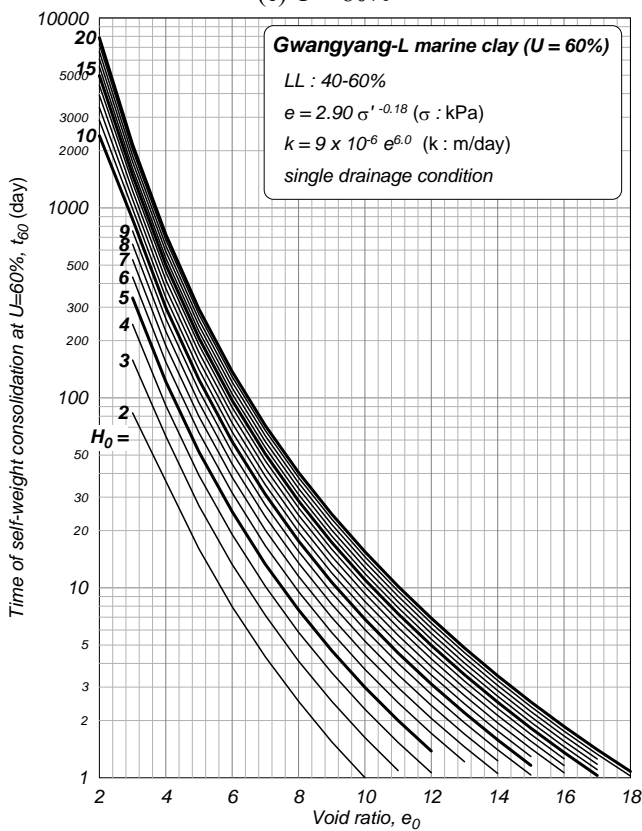
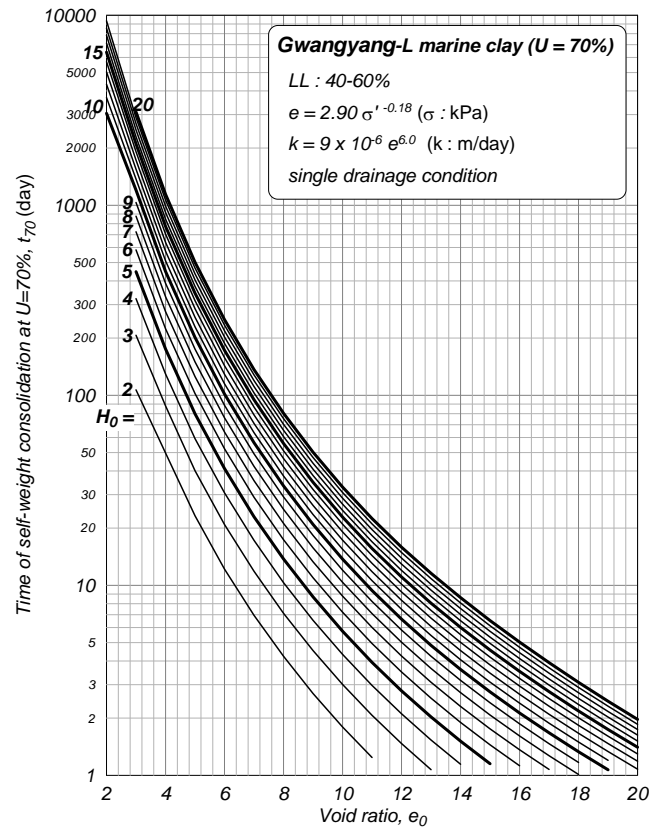
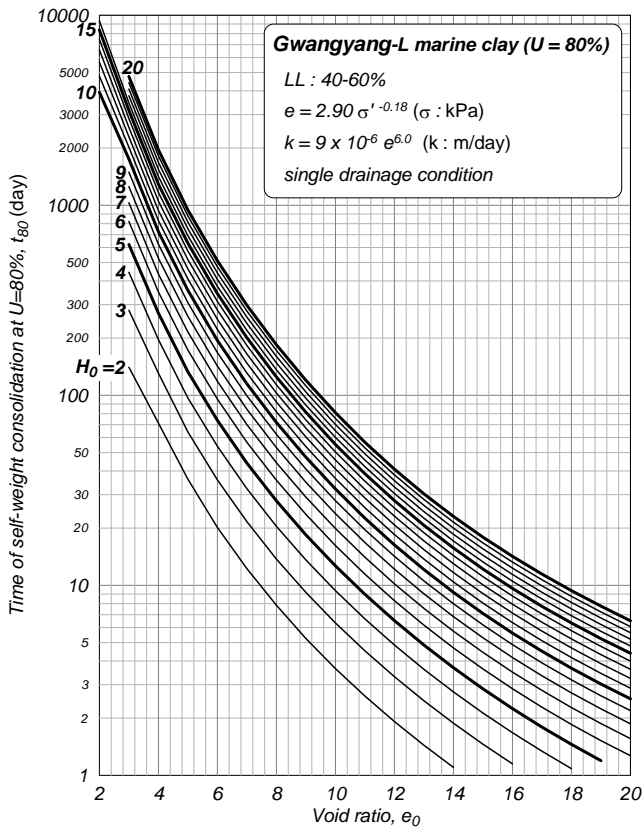
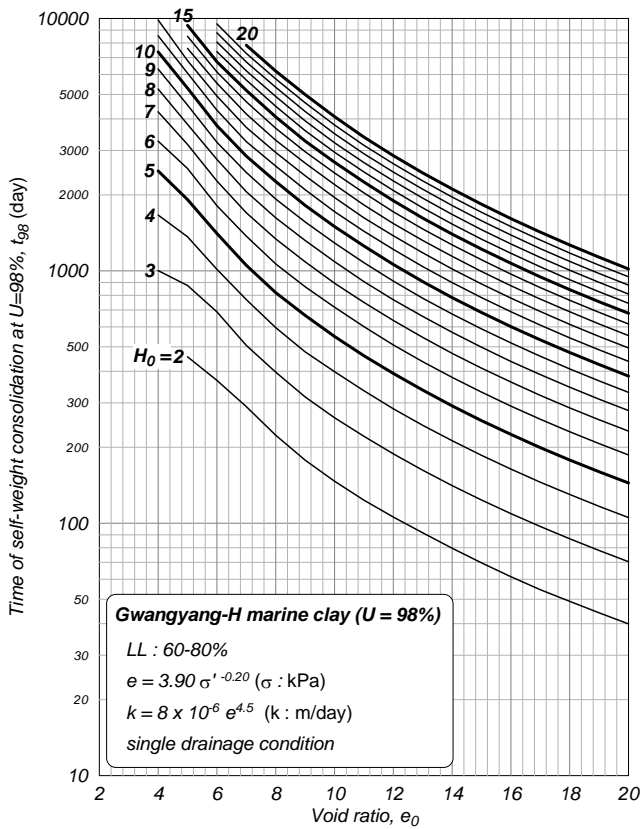
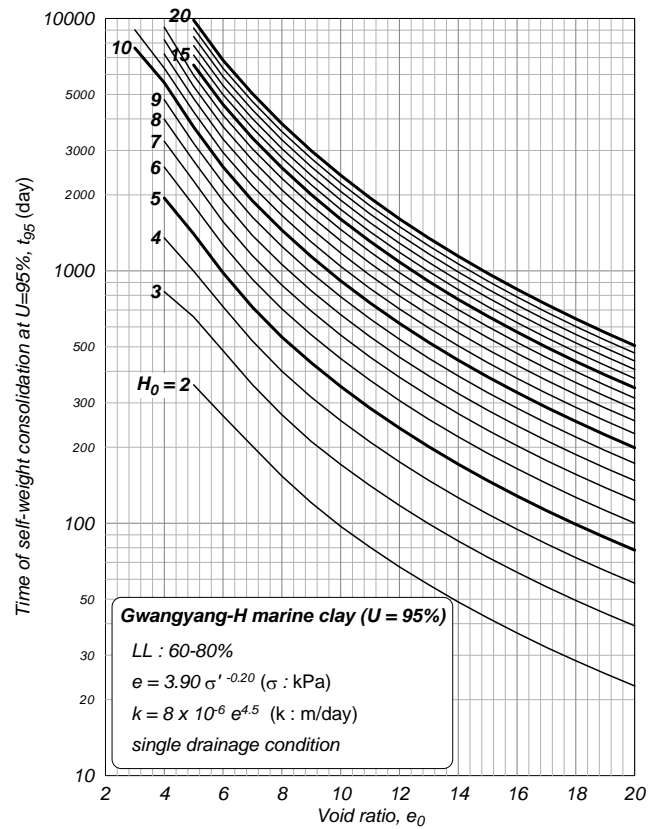


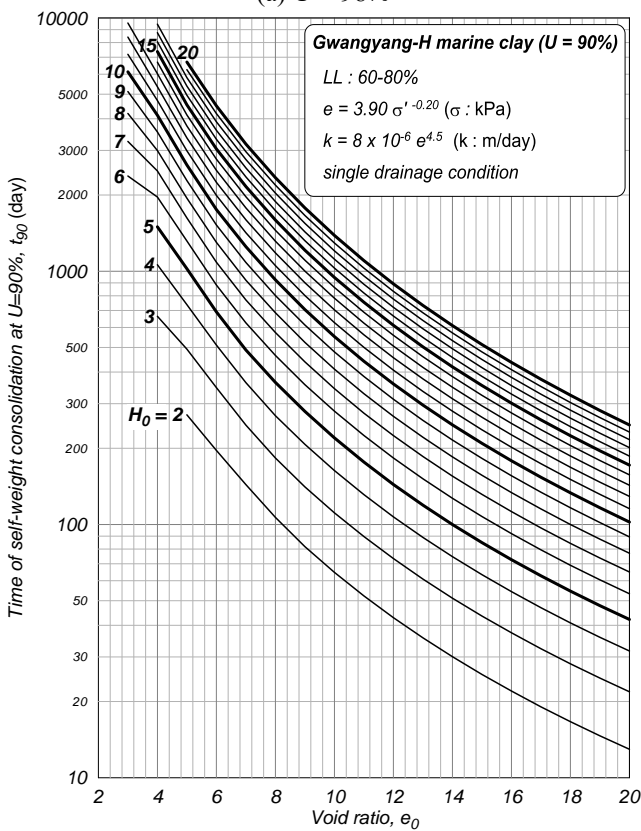
Fig. A3 Design chart of the consolidation time for Gwangyang L marine clay



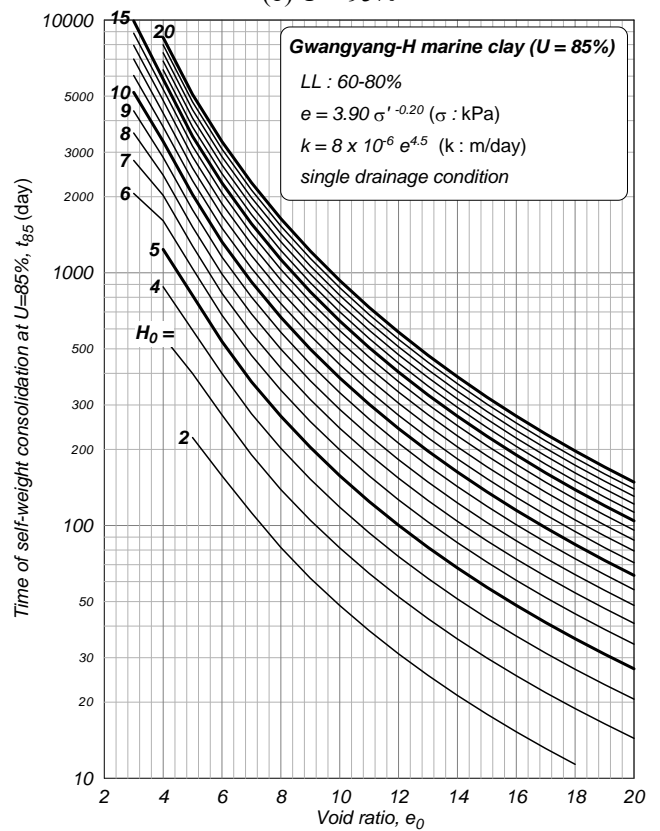
(a) U = 98%



(b) U = 95%

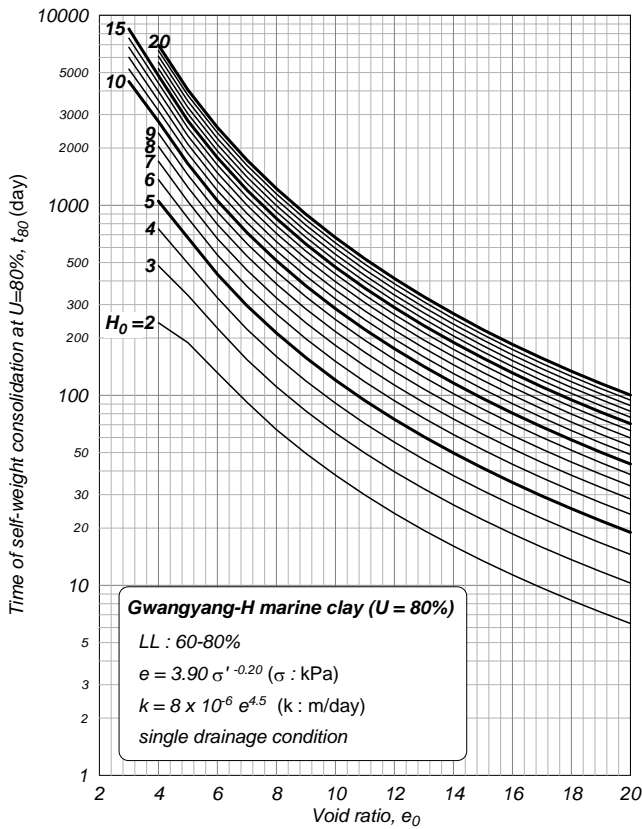


(c) U = 90%

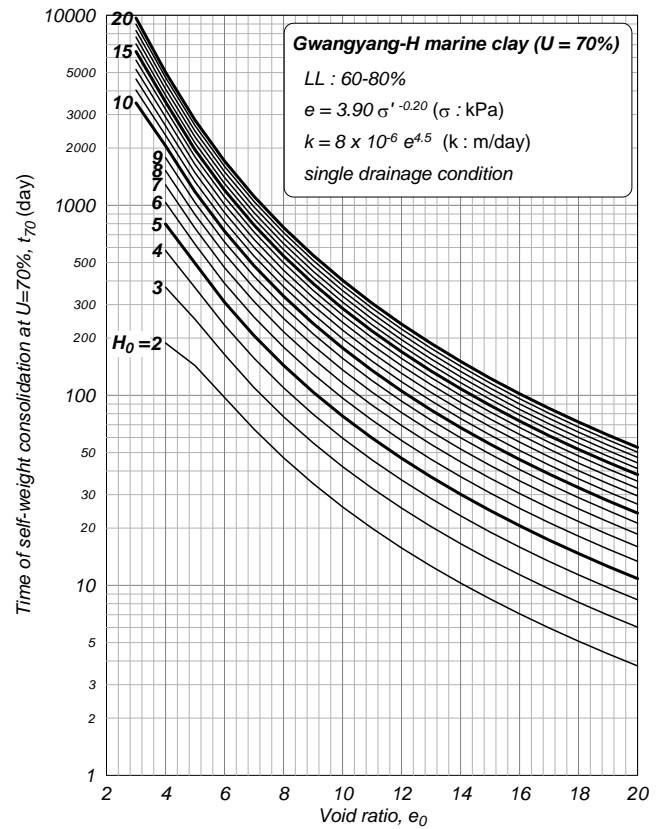


(d) U = 85%

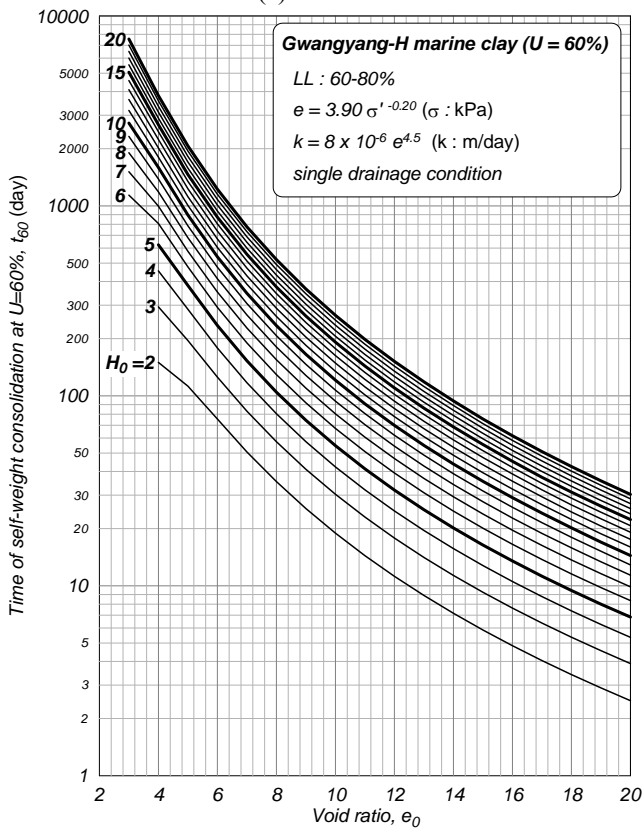
Fig. A4 Design chart of the consolidation time for Gwangyang H marine clay (continue)



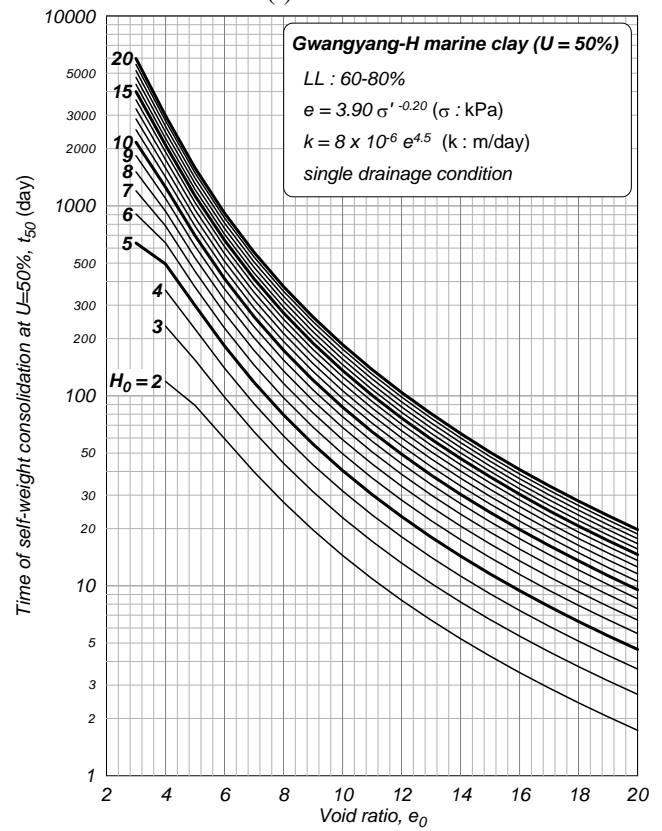
(e) $U = 80\%$



(f) $U = 70\%$



(g) $U = 60\%$



(h) $U = 50\%$

Fig. A4 Design chart of the consolidation time for Gwangyang H marine clay

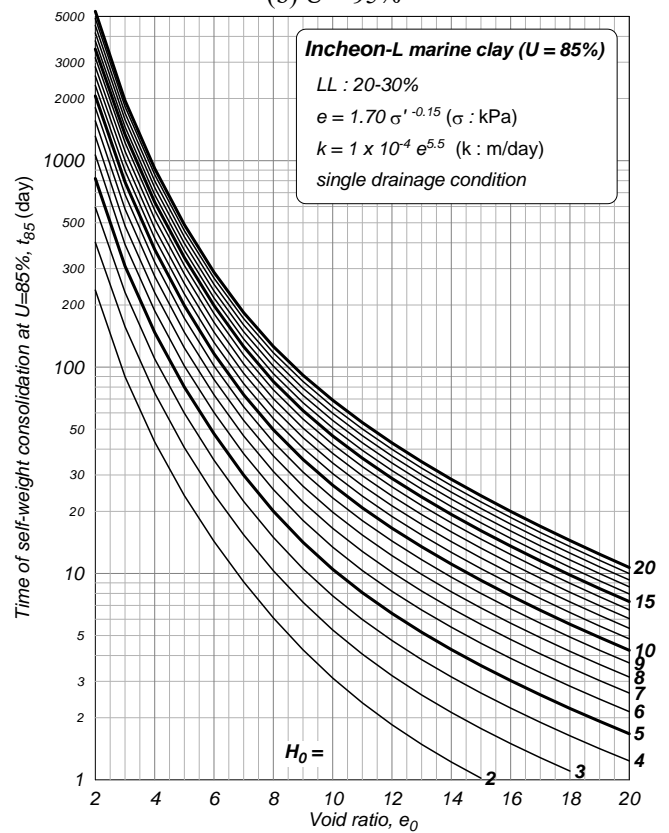
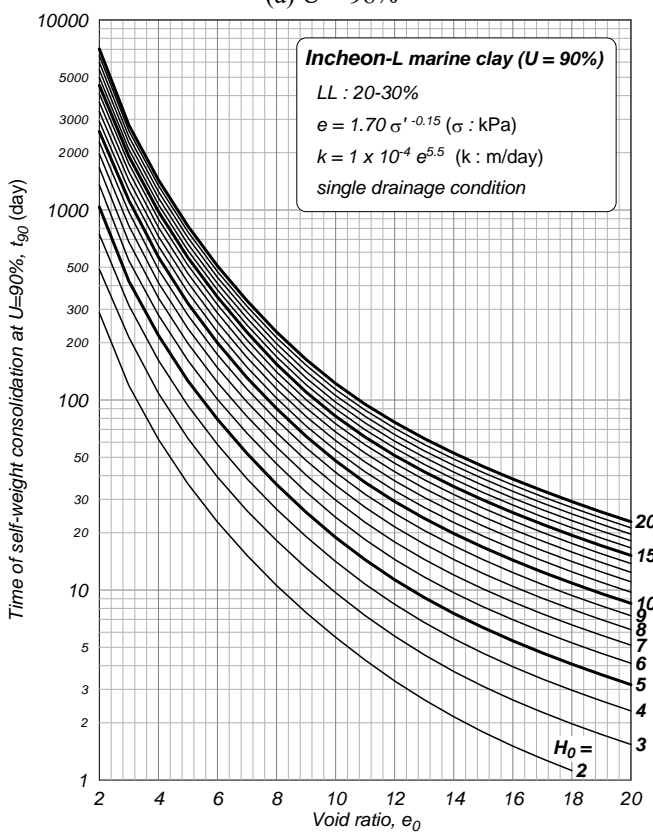
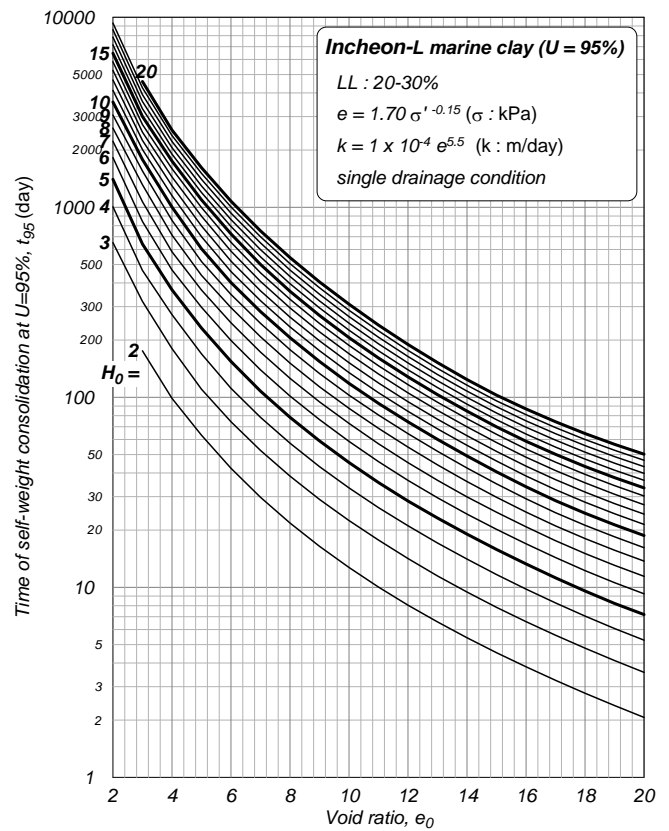
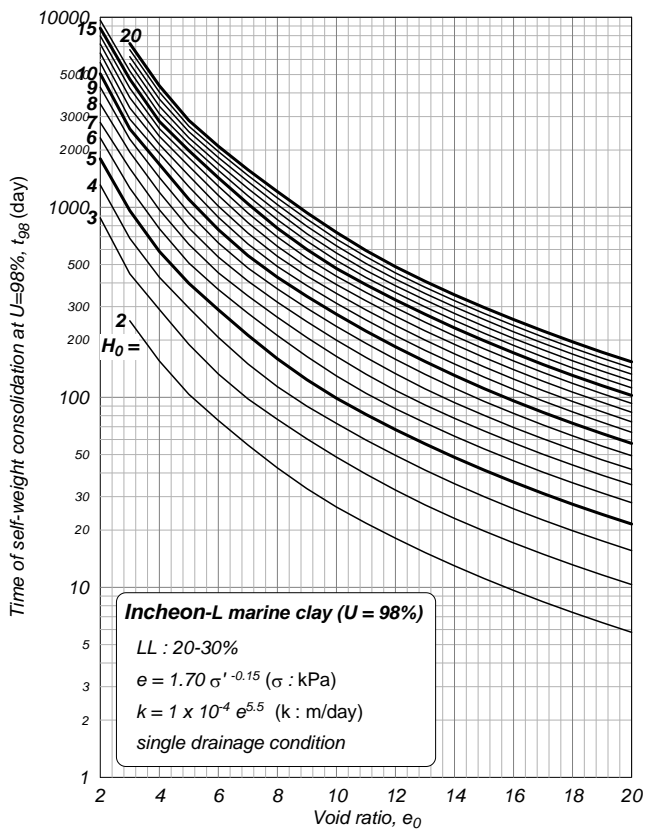


Fig. A5 Design chart of the consolidation time for Incheon L marine clay (continue)

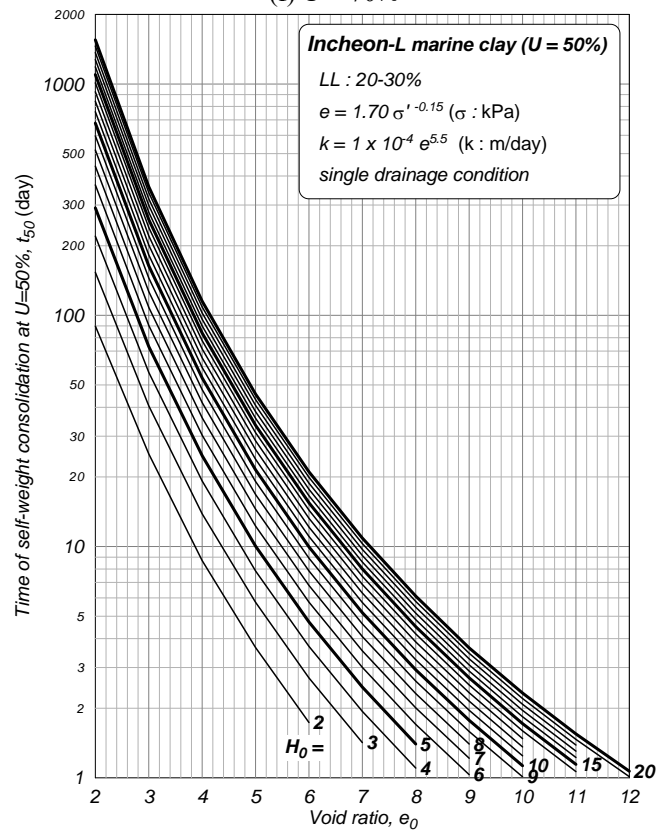
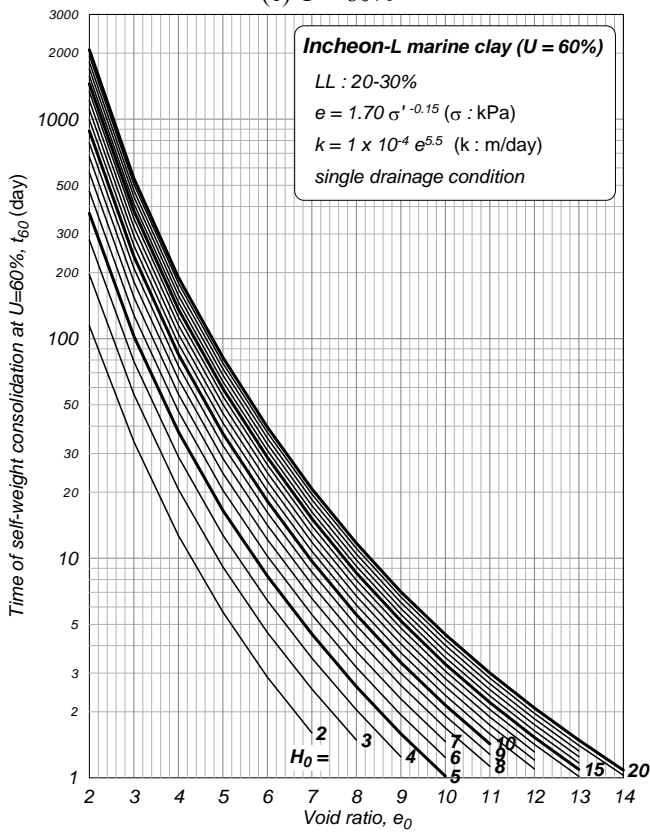
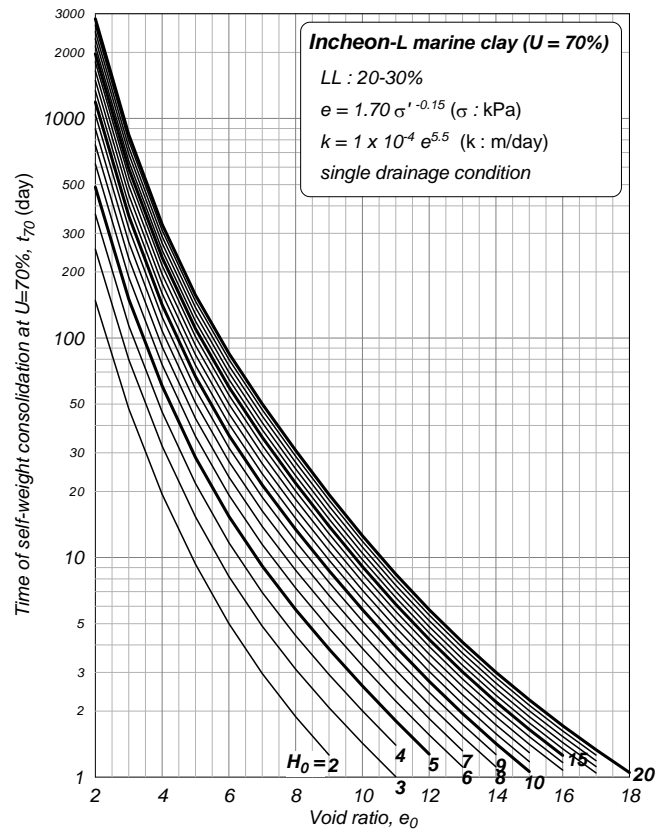
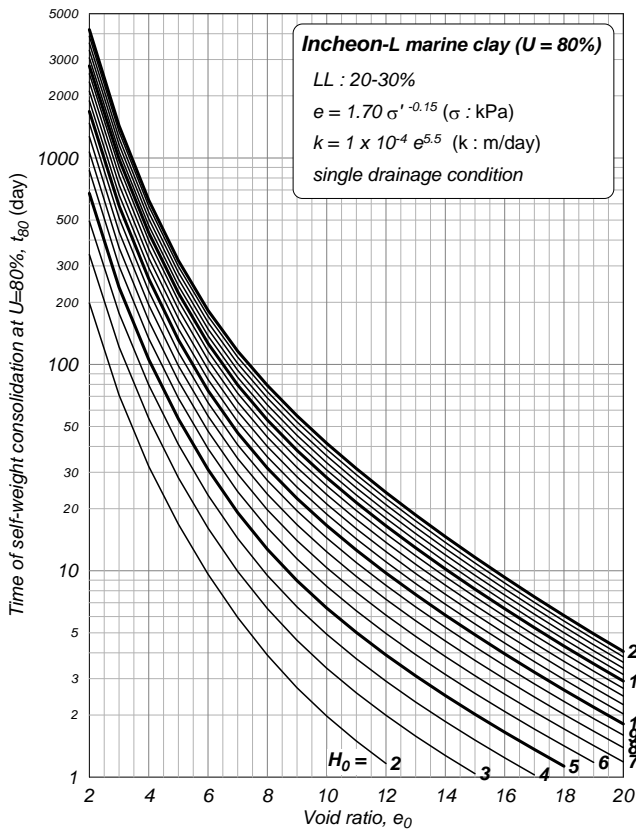
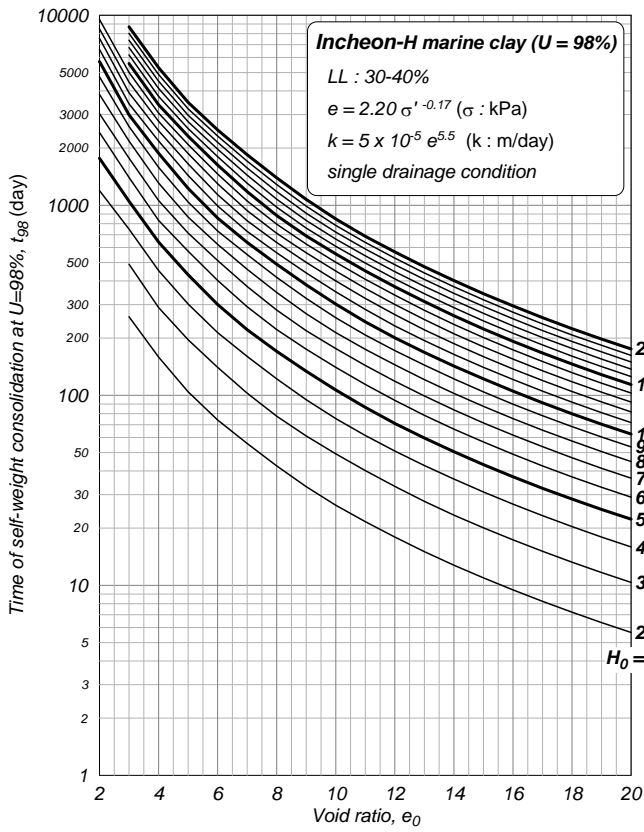
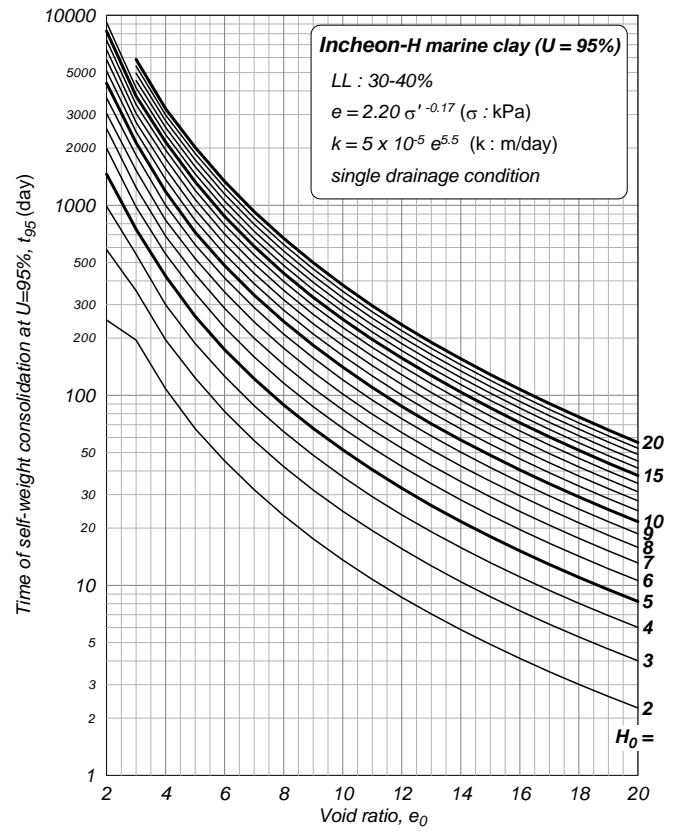


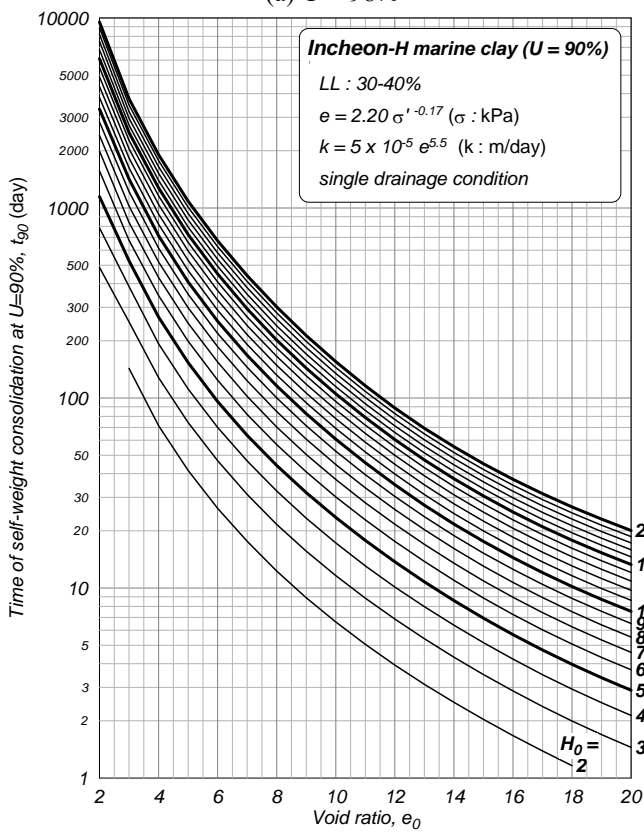
Fig. A5 Design chart of the consolidation time for Incheon L marine clay



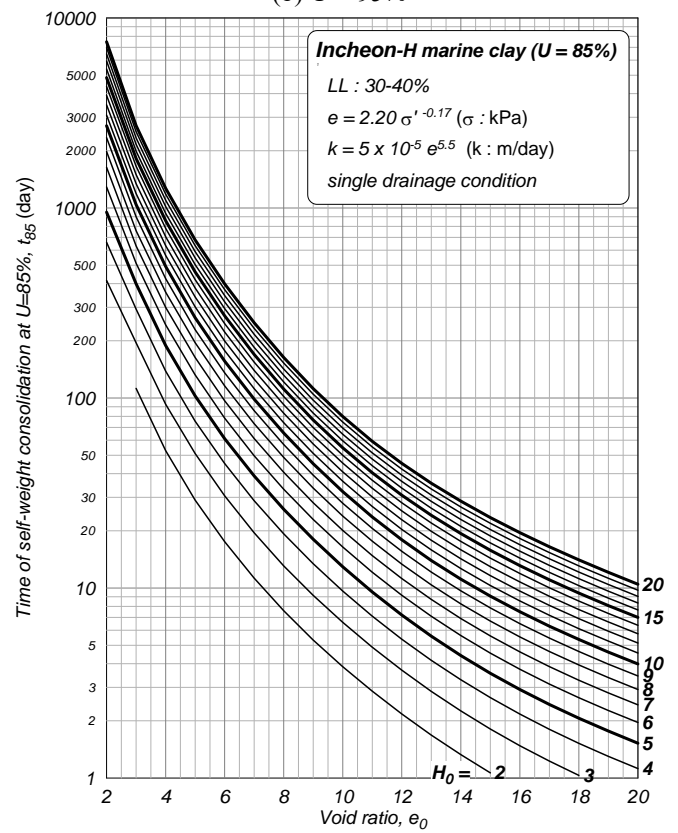
(a) U = 98%



(b) U = 95%



(c) U = 90%



(d) U = 85%

Fig. A6 Design chart of the consolidation time for Incheon H marine clay (continue)

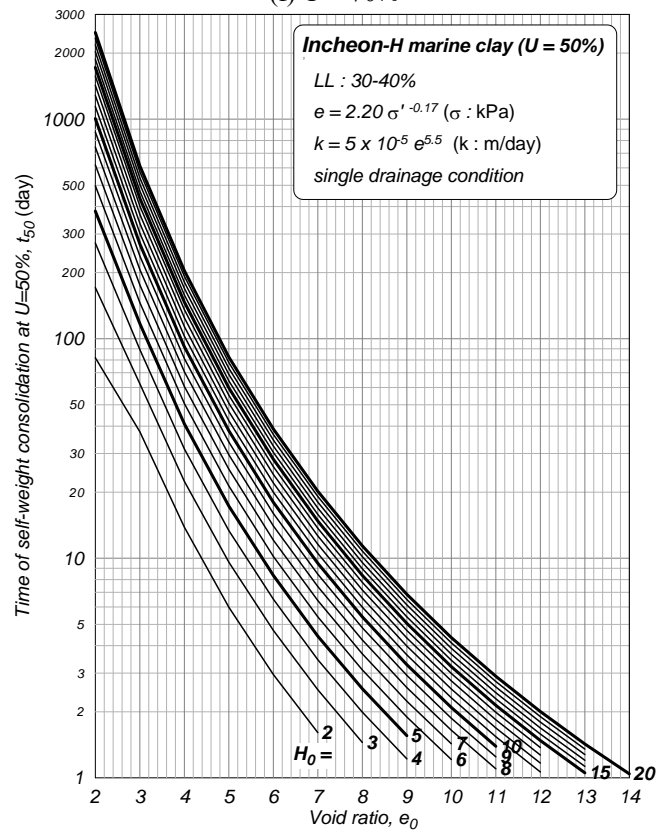
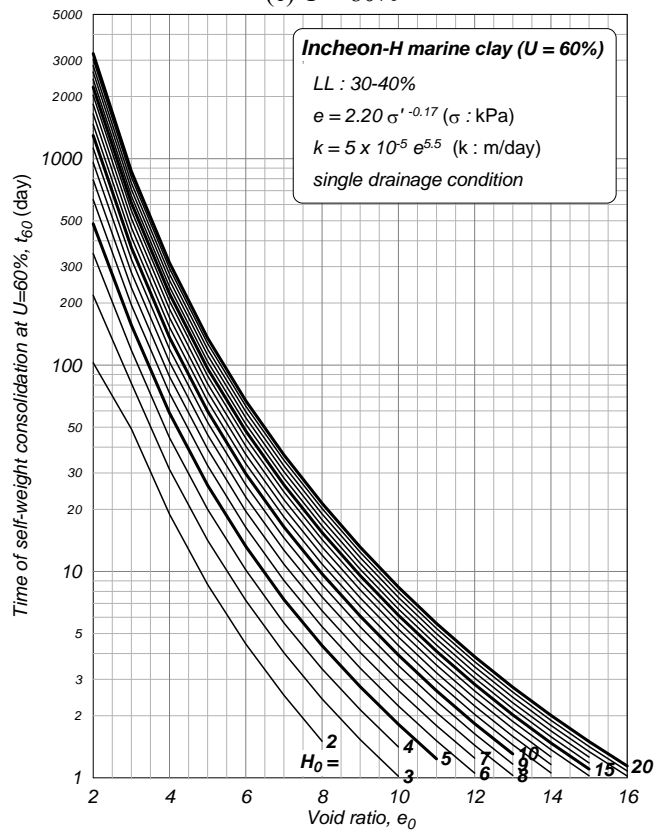
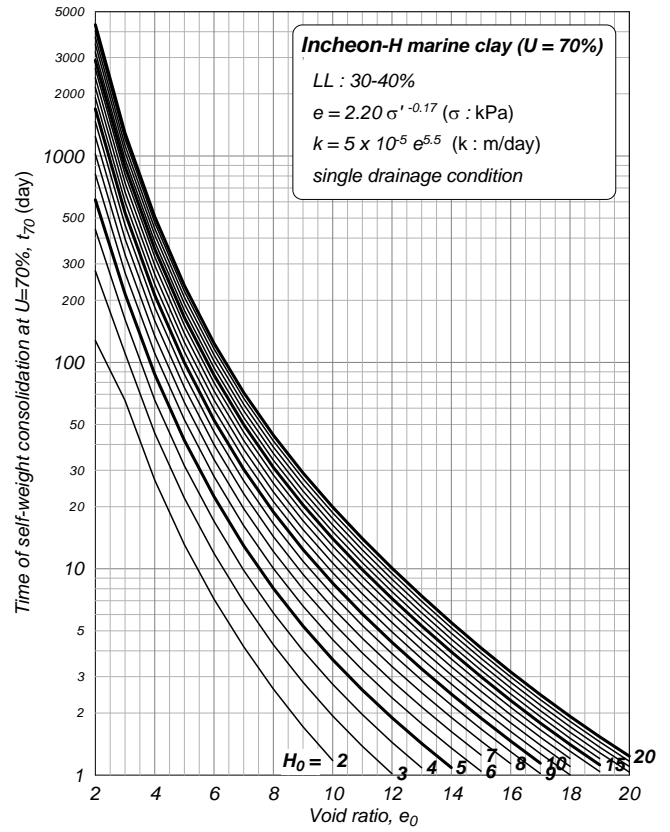
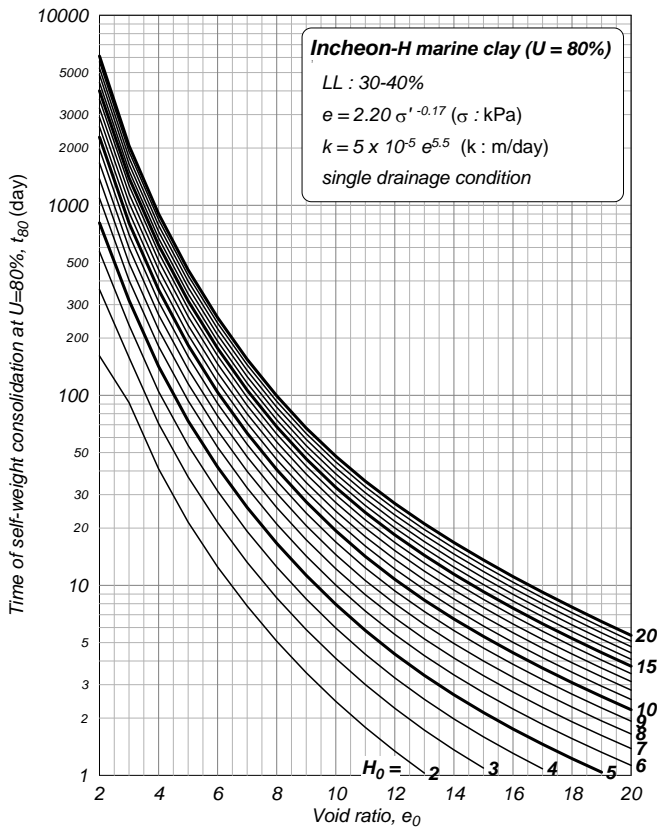


Fig. A6 Design chart of the consolidation time for Incheon H marine clay