

FACTORS AFFECTING FIELD SETTLEMENT EVALUATION OF PREFABRICATED VERTICAL DRAINS PERFORMANCE IN SOFT BANGKOK CLAY BY ASAOKA AND HYPERBOLIC METHODS

Sinat Koslanant¹, Chaiyasat Sakulsaksri^{2,*} and Chaiyathawat Boonyong¹

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Abstract

The study highlights the importance of these factors in field settlement evaluation and back-calculating the horizontal drainage consolidation coefficient in Bangkok clay. Longer evaluation periods induce higher ultimate settlement and lower consolidation degrees with the Asaoka method, while the Hyperbolic method predicts constant values. The coefficient of consolidation in horizontal drainage back-analyzed by the Asaoka method decreases with longer evaluation periods but is similar to CRS-R at the final stress level. Both methods' predicted settlement versus time curves agree well with field curves, especially for longer evaluation periods. Therefore, the paper recommends adopting the settlement versus time curves predicted by both methods for their simplicity and proficiency in practice. These findings provide valuable insights for evaluating the degree of consolidation and improving soft clay using prefabricated vertical drains, especially in areas with similar soil conditions.

Keywords: Asaoka Method; Field Settlement; Hyperbolic Method; Prefabricated Vertical Drains; Soft Bangkok Clay

Introduction

A large amount of ground improvement projects has been carried out to develop lands in many parts of the world. During the last three decades, prefabricated vertical drains (PVD) with preloading have been extensively used to improve soft soil deposits due to its economical and simple technique. The installation of PVD with preloading provides

artificial drainage path in horizontal direction to accelerate the consolidation process. After the preloading completes, water in the clay layer begins to flow owing to the gradient caused by the excess pore pressure. The clay layer undergoes further settlement due to its volume decreases as stress is transferred from excess pore pressure to effective

¹ Department of civil engineering, Faculty of Industrial technology, Rambhai Barni Rajabhat University, Chanthaburi, 22000, Thailand. Email: sinat.k@rbru.ac.th; chaiyathawat.b@rbru.ac.th

² Department of Civil and Environmental Engineering Technology, College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok, 10800, Thailand. Email: chaiyasat.s@cit.kmutnb.ac.th*

* Corresponding author

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stress. Accordingly, this technique could be used to minimize the post construction settlement from primary consolidation and also to greatly reduce the secondary compression. In such ground improvement, an average degree of consolidation is an important parameter used as one of design criteria prior to surcharge removal. This average degree is usually obtained as a ratio of soil settlement at a specific time over ultimate consolidation settlement. The settlement at a specific time is observed and the ultimate consolidation settlement is predicted. A coefficient of horizontal consolidation also plays a significant role for predicting the settlement rate. As soil properties are extremely varied in the field, it is difficult to reliably determine the ultimate consolidation settlement by using the e -log σ'_v curve and the coefficient of horizontal consolidation from laboratory tests, such as Rowe cell and constant rate of strain consolidometer with radial drainage (CRS-R), and reliably apply the time-settlement curve by Barron's equation (Barron, 1948). Thus, in practice, the observational methods such as the Asaoka method (Asaoka, 1978) and the Hyperbolic method (Tan, 1995) are adopted to predict the ultimate consolidation settlement and the coefficient of horizontal consolidation. However, from the previous researches, Arulrajah *et al.* (2003, 2004); Arulrajah and Bo, (2008) found that settlement prediction by these observational methods would be affected by various factors including selection of time interval as well as evaluation period at Changi international airport for Singapore clay. The magnitude of ultimate settlement decreases and the degree of consolidation subsequently increases as a longer period of evaluation is used in the prediction by the Asaoka method (Arulrajah *et al.*, 2003). The magnitude of ultimate settlement increases and subsequently the degree of consolidation decreases as a longer period of assessment is used in the prediction by the Hyperbolic method (Arulrajah *et al.*, 2003). Unlike the Bangkok clay deposit having smectite as its major clay mineral composite, the main clay mineral in Singapore clay deposit is kaolinite (Tanaka *et al.*, 2001). There are relatively differences in the soil properties including water content, Atterberg's limits, coefficients of consolidation, thickness of these deposits and so on (Tanaka *et al.*, 2001; Seah *et al.*, 2004; Arulrajah and Bo, 2008). Although several projects of ground improvement by PVD with preloading were carried out in Bangkok, the factors affecting field settlement evaluation have not been investigated yet. Hence, it is worth to examine how these factors affect the settlement prediction of Bangkok clay. The aim of this study is to emphasize the significance and influence of various factors that

affect predictions by the Asaoka, Hyperbolic evaluation methods in soft Bangkok clay.

The case study of ground improvement for the airside pavement phase 1 project was selected to study due to the availability of field monitoring data throughout the construction period. It was the first ground improvement project of the construction of Suvarnabhumi International Airport (SIA) completed in 2003. The SIA was opened to the public in 2006. The location of the SIA was shown in Figure 1.

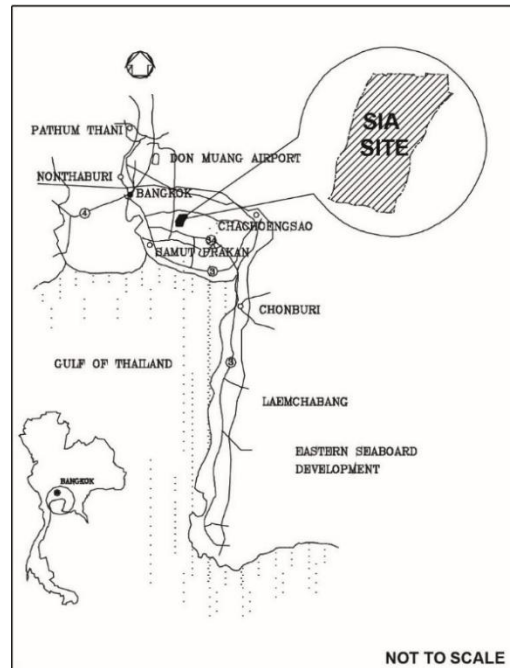


Figure 1. Location of Suvarnabhumi international airport

The ground improvement area of the airside pavement was about 320 hectare including West Runway, Cross Taxiways, Apron, part of East Taxiway and two Emergency Access roads as shown in Figure 2 with construction cost of about 8,240 million Baht (264 million USD). The procedures of the ground improvement construction were consisted of various steps including site clearing, leveling and backfilling to level at mean sea level (MSL), placing the 1st layer filter fabric (on original ground), constructing sand blanket to level of 1 m above MSL with drainage facilities installation, installing PVD with 1 m $\times$ 1 m spacing in square pattern, constructing the 2nd sand blanket to and constructing crushed rock surcharge fill (in two stages) to accelerate the consolidation process of soft Bangkok clay, respectively. After consolidation process was complete, crushed rock was removed and reused in other areas. It thickness and left for 3 months waiting period to level of 1.5 m above MSL, placing the 2nd

layer filter fabric (on the top of the sand blanket layer), should be noted that the counterweight berms with 1.7 m height and 15.4 m width were also constructed to stabilize the preloading embankment. The embankment construction at the 1st stage was to reach a total of 2.8 m fill increase subsoil's strength prior to the next stage of construction. The final preloading height under 75 kPa or 85 kPa was 3.6 m with 6 months periods. The surcharge pressure of 85 kPa was waiting period or 4.1 m with 11 months waiting required as preloading of Aircraft Stands in Apron area closed to Terminal Building as shown in Figure 2. The settlement data from the four settlement plates at the Aircraft Stands were

investigated and used as field data samples in the evaluation process because of their longer waiting period than other areas. A typical embankment section is shown in Figure 3. The field settlement data were plotted as shown in Figures 4-7. The degree of consolidation was analyzed at 6, 9, and 12 months after surcharge placement. To evaluate the settlement prediction with the Asaoka method, various time intervals from 7 to 56 days were used in the analysis. Accordingly, the prediction of settlement versus time curves in soft Bangkok clay was back-analyzed with the different time intervals and the various evaluation periods.

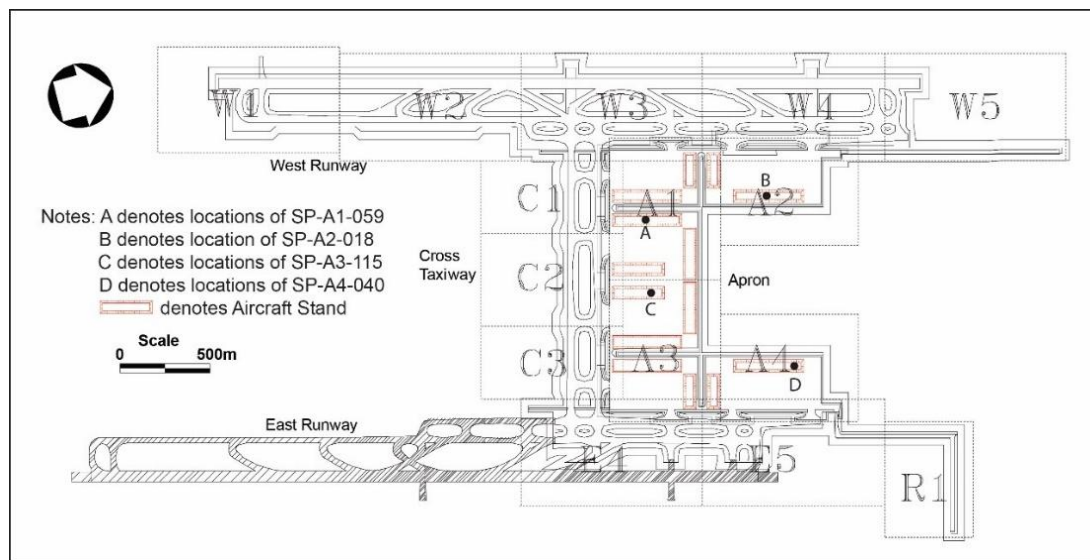


Figure 2. Locations of the selected settlement plates

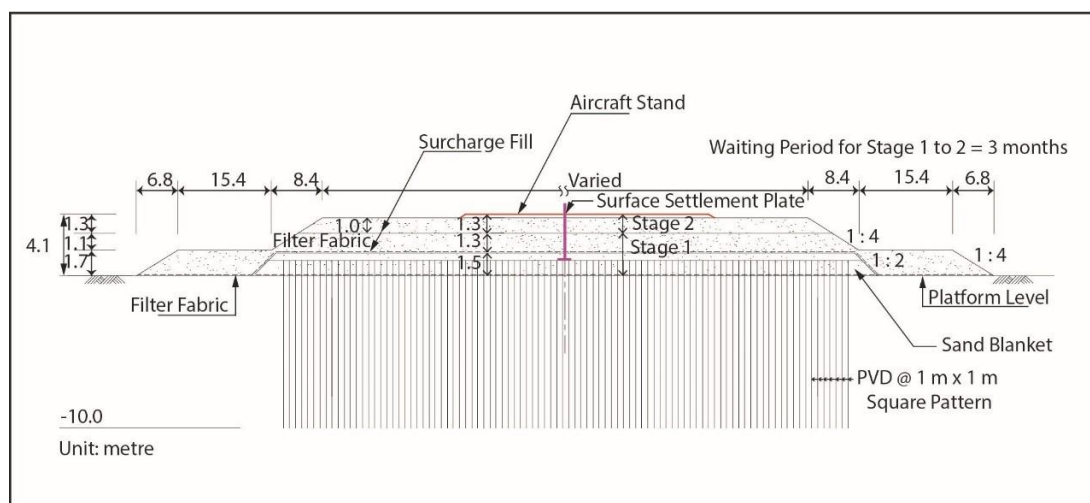


Figure 3. Typical cross section of embankment

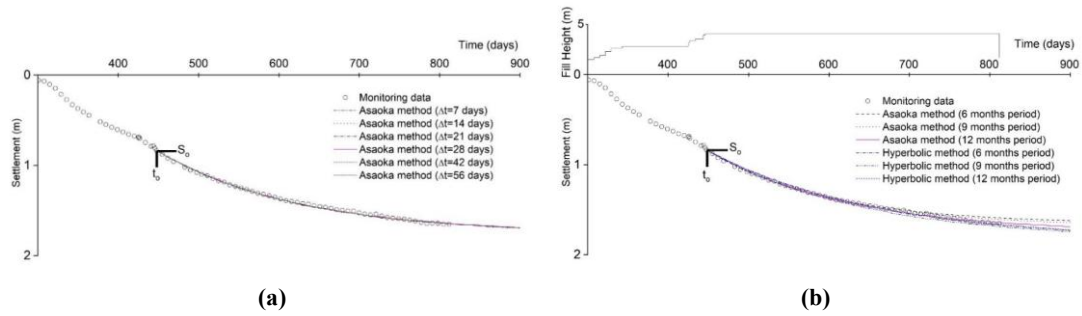


Figure 4. (a) Asaoka method with 28 days interval and Hyperbolic method at various period, Time line of construction and field settlement at SP-A1-059 and (b) Asaoka method with different time intervals at 12 months after preloading, Time line of construction and field settlement at SP-A1-059

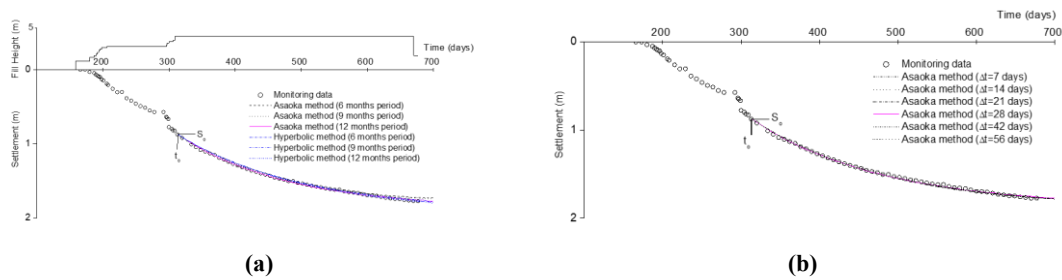


Figure 5. (a) Asaoka method with 28 days interval and Hyperbolic method at various periods, Time line of construction and field settlement at SP-A2-018 and (b) Asaoka method with different time intervals at 12 months after preloading, Time line of construction and field settlement at SP-A2-018

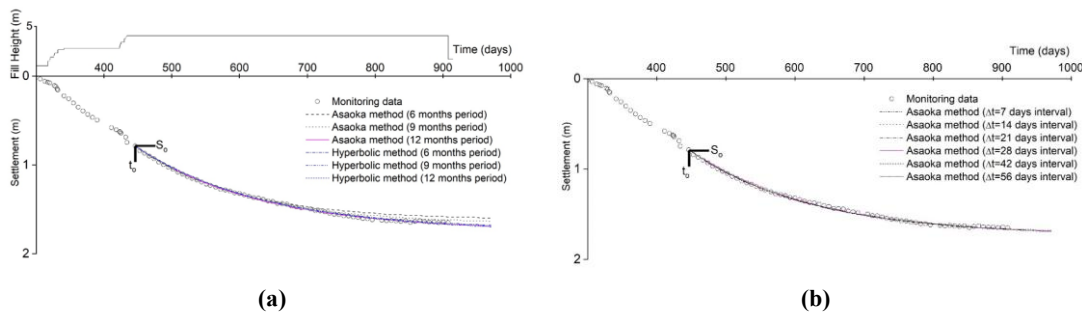


Figure 6. (a) Asaoka method with 28 days interval and Hyperbolic method at various periods, Time line of construction and field settlement at SP-A3-115 and (b) Asaoka method with different time intervals at 12 months after preloading, Time line of construction and field settlement at SP-A3-115

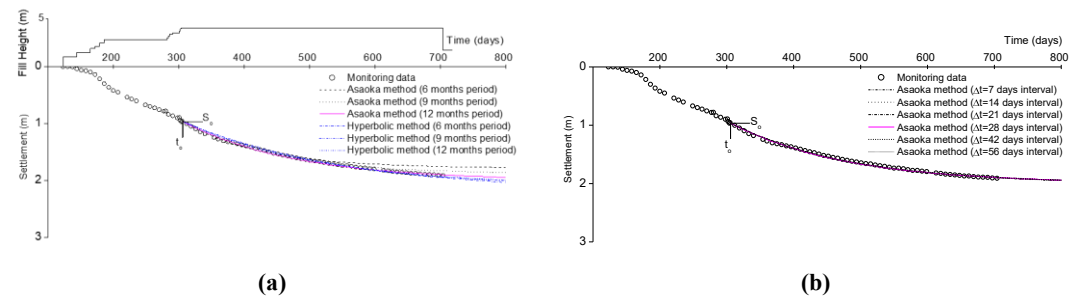


Figure 7. (a) Asaoka method with 28 days interval and Hyperbolic method at various periods, Time line of construction and field settlement at SP-A4-040 and (b) Asaoka method with different time intervals at 12 months after preloading, Time line of construction and field settlement at SP-A4-040

Subsoil Condition

The subsoil condition of the SIA site situated on the Bangkok clay deposit, which is the upper sequence that distributes over the lower central lain (Chao Phraya Plain) including Bangkok metropolitan (Sinsakul, 2000). It is the landform where Chao Phraya River interacted with marine processes related to the sea-level changes in the Holocene transgression. It predominantly consists of 3 layers of clay. The lower layer composes of dense sandy clay in light gray deposited in the estuarine environment. The middle layer consists of silty clay with abundant of plant remains and small amount of shell fragments deposited in the intertidal environment. The uppermost layer composes of soft silty clay in greenish gray with abundant shell fragments deposited in the shallow marine environment.

The thickness of the Bangkok clay varies from 15 m to 25 m. Prior to the project commenced, the subsoil investigation including 74 soil sampling boreholes, 175 field vane shear tests and 357 Piezocone Penetration tests was conducted throughout the ground improvement areas. Generally, the subsoil condition is relatively uniform composing of four different layers within the depth of 20 m namely: weather crust formed by cyclic wetting process and natural cementation with thickness of 1 m to 2 m, underlaid by the greenish grey very soft to soft clay layer with thickness of 8 m to 10 m, then following by the light grey medium stiff clay and stiff clay layer lying between 11 m to 15 m below the original ground surface, and the last layer of light grey to light brown stiff clay below the depth of 15 m (TMSUM, 2002). The changes of physical properties with depth are associated with the increasing silt or fine sand content and decreasing of clay fraction. The major concern of

the ground improvement work was the very soft to soft clay layer with high water content, low undrained shear strength and high compressibility. The general properties of soil profiles up to 20 m depth are illustrated in Figure 8 (Seah *et al.*, 2004).

Evaluation by field settlement

The Asaoka and Hyperbolic methods also shall be applied to find the consolidation coefficient in horizontal drainage by back analysis. These two methods are often used in the evaluation of degree of ground improvement by preloading with PVD (Orleach, 1983; Bergado *et al.*, 1993; Seah *et al.*, 2004; Mesri and Huvaj-Sarihan, 2009; Chung *et al.*, 2009).

The Asaoka method

Asaoka (1978) proposed a graphical solution for consolidation problems with PVD by using Barron (1948) equations in horizontal drainage. The procedure is simple as follows: (i) plot the observed settlement against the elapsed time, (ii) select the series of settlement $S_1, S_2, S_3, \dots, S_{i-1}, S_i$, respectively at time $t_1, t_2, t_3, \dots, t_{i-1}, t_i$ such that $t_i - t_{i-1} = \Delta t = \text{constant}$ and S_i is the observed settlement at time t_i , (iii) plot S_i against S_{i-1} to obtain a straight line, and (iv) extrapolate the line to intersect a 45° line through the origin.

The point of intersection is the ultimate settlement, S_{ult} . The straight line can be written in linear equation as:

$$S_i = S_0 + \beta S_{i-1} \quad (1)$$

where S_0 and β are the y intercept and the slope of the straight line, respectively.

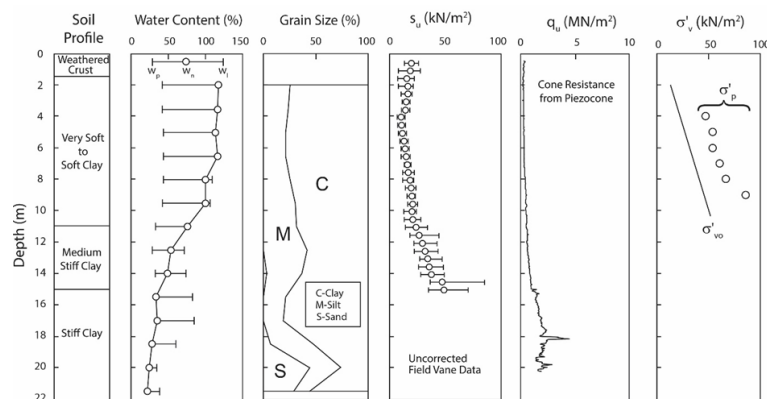


Figure 8. Soil profiles at Suvarnabhumi international airport (Seah *et al.*, 2004)

The ultimate settlement can be calculated as:

$$c_h = \frac{-\ln \beta d_e^2 \mu}{8\Delta t} \quad (10)$$

$$S_{ult} = \frac{S_0}{1-\beta} \quad (2)$$

Replace equation (10) into the equation (5):

From observed settlement and ultimate settlement calculated from equation (2), consolidation degree computed by the settlement ratio can be estimated.

$$S_i = S_{ult} \left[1 - \exp\left(\frac{\ln \beta t_i}{\Delta t}\right) \right] \quad (11)$$

Accordingly, the coefficient of horizontal consolidation, the ultimate settlement and the time-settlement curve can be determined from this method.

$$U_{i\%} = \frac{S_i}{S_{ult}} \times 100\% \quad (3)$$

where U_i is the consolidation degree computed by the settlement ratio at time t_i .

The Hyperbolic method

The coefficient of consolidation in horizontal drainage (c_h) can be obtained from the Barron (1948) equal-strain settlement versus time relationship, modified to include the effects of spacing, smear and well resistance (Hansbo, 1979) as follows.

The calculation of the ultimate settlement in one-dimensional consolidation estimated from a rectangular Hyperbolic plot of time/settlement versus time, of a settlement record for vertical drainage has been proposed by Sridharan and Sreepada (1981). Sridharan *et al.* (1987) have obtained the coefficient of consolidation, c_v from oedometer tests, by fitting laboratory settlement data in form of time/settlement versus time plot to the linear segment of the Hyperbolic plot between the consolidation degrees of 60% (U_{60}) and 90% (U_{90}) points of the theoretical time factor/consolidation degree versus time factor in vertical consolidation plot. Similarly, the extension of the proposed method based on the same assumptions was adopted for prefabricated vertical drains by Tan (1995) as below.

$$U_i = 1 - \exp\left(\frac{-8c_h t_i}{\mu d_e^2}\right) \quad (4)$$

Replace $U_i = \frac{S_i}{S_{ult}}$ from equation (3) in the equation (4):

$$S_i = S_{ult} \left[1 - \exp\left(\frac{-8c_h t_i}{\mu d_e^2}\right) \right] \quad (5)$$

Where:

$$\frac{T_{ri}}{U_i} = MT_{ri} + D \quad (12)$$

$$\mu = F_n + F_s + F_r \quad (6)$$

F_n is the factor for PVD spacing effects,
 F_s is the factor for smear effects,
 F_r is the factor for well resistance effects.

where T_n is time factor for horizontal consolidation corresponding to U_i . M and D are slope and interception of linear segment in the plot for the consolidation degrees between 60% and 90%. Relationship between c_h and T_h is given in equation (13).

Consider the settlements at time $t = t_i$ [equation (5)] and $t = t_{i-1}$ [equation (7)]

$$c_h = \frac{T_h d_e^2}{t} \quad (13)$$

$$S_{i-1} = S_{ult} \left[1 - \exp\left(\frac{-8c_r t_{i-1}}{\mu d_e^2}\right) \right] \quad (7)$$

Rewrite equations (5) and (7) and divide:

Replace equation (13) into equation (4), then relationship between U_i and T_{ri} can be obtained as:

$$\frac{S_{ult} - S_i}{S_{ult} - S_{i-1}} = \exp\left[\frac{-8c_r}{\mu d_e^2}(t_i - t_{i-1})\right] \quad (8)$$

$$U_i = 1 - \exp\left(\frac{-8T_{hi}}{\mu}\right) \quad (14)$$

Replace $\frac{S_{ult} - S_i}{S_{ult} - S_{i-1}} = \beta$ the slope of the straight line and $t_i - t_{i-1} = \Delta t$ (the selected time interval):

A Hyperbolic relationship between monitoring settlement (S_i) and consolidation time (t), in linear segment for the consolidation degrees between 60% and 90% is:

$$\ln \beta = \frac{8c_r}{\mu d_e^2} \Delta t \quad (9)$$

$$\frac{t_i}{S_i} = mt_i + d \text{ or } S_i = \frac{t_i}{mt_i + d} \quad (15)$$

and

Where m and d are slope and interception of linear segment in the plot for the consolidation degrees between 60% and 90%.

Thus, the settlement at the end of primary consolidation (S_{100}) is defined as

$$\lim_{t \rightarrow \infty} S_i = \lim_{t \rightarrow \infty} \frac{t_i}{mt_i + d} = S_{100} = \frac{1}{m} \quad (16)$$

However, according to Tan (1995), the end of primary settlement from the equation (16) was overestimated and unacceptable. Therefore, the settlement at the end of primary consolidation obtained from equation (17) was recommended instead.

$$S_{100} = \frac{M}{m} = \frac{S_{60}}{0.6} = \frac{S_{90}}{0.9} \quad (17)$$

where S_{60} and S_{90} are settlement at the consolidation degrees of 60% and 90%, respectively.

Hence, the coefficient of horizontal consolidation, the ultimate settlement can be calculated from this method.

Results and Discussion

Factors affecting evaluation by the Asaoka method

Field settlement data were selected from the four settlement plates including SP-A1-057, SP-A2-018, SP-A3-115 and SP-A4-040 at the Aircraft Stands in the Apron area located as shown in Figure 2. These data were analyzed to study the various factors affecting on the predictions of the ultimate settlement, the settlement versus time curve, the degree of consolidation and the coefficient of consolidation in horizontal drainage. The analysis process was described below.

1. Settlement data from SP-A1-059 were plotted in relationship between S_{i-1} and S_i as shown in Figure 9 with different time intervals during period of 12 months.

2. Linear regression analysis was applied to draw a trend line with linear equation and R^2 for the graph. The slope (β) and interception (S_0) of the graph can be estimated from the equation.

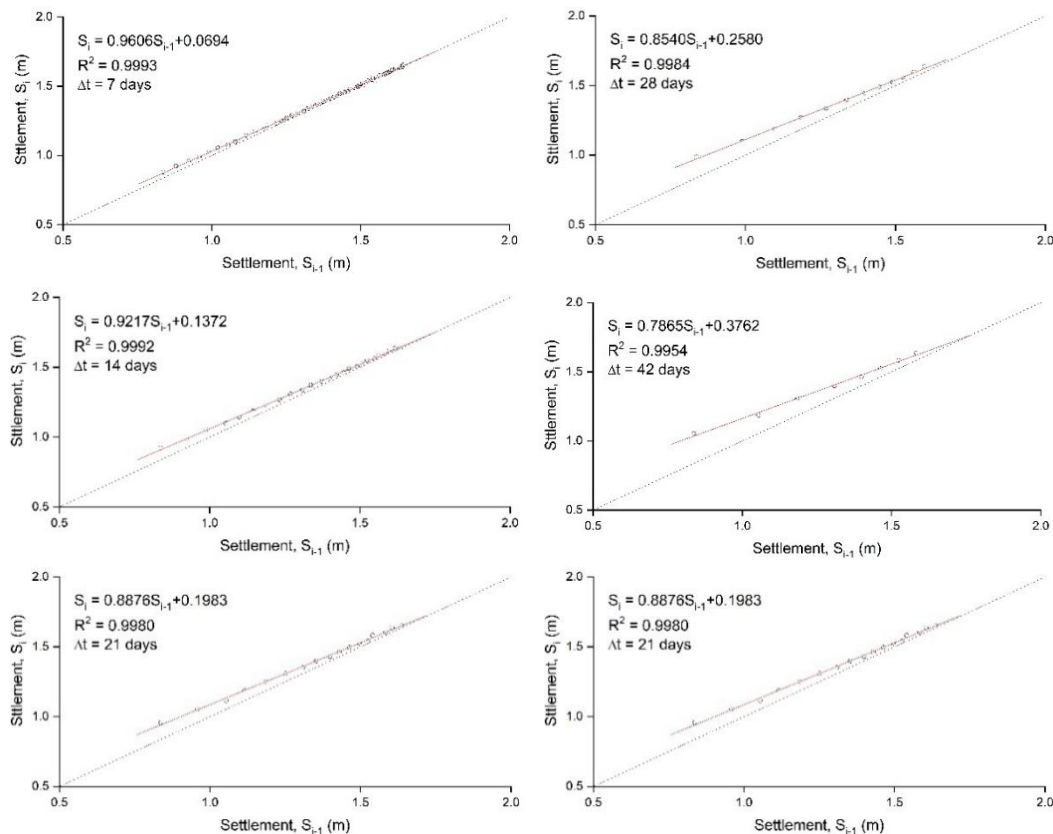


Figure 9. Asaoka plots of SP-A1-059 with the various time intervals at 12 months after preloading

Then, the ultimate settlement was determined by the equation (2) or by the interception point between the trend line and the 45° line.

3. Changed the time intervals and the time periods of settlement data as specified. The ultimate settlements were tabulated in Tables 1 to 4 for the selected settlement plates.

4. Consolidation degree was obtained from equation (3). The results were also tabulated in Tables 1 to 4.

5. Coefficient of consolidation in horizontal drainage could be estimated by replacing the graph slope (β) from equation (10) with:

$$F_n = \ln\left(\frac{d_e}{d_w}\right) - 0.75 = 2.09$$

($d_e = 1.13$; $S = 1$ m. and $d_w = 0.066$ m)

where d_e is equivalent diameter of influence zone of PVD, d_w is equivalent diameter of PVD; $F_s = \left(\frac{k_h}{k_s} - 1\right) \ln(s) = 0.28$, ($\frac{k_h}{k_s} \approx 1.4$ from consolidation test at final vertical stress, and $S = \frac{d_s}{d_w} = 2$ based on recommendation by Hansbo, 1979),

where k_h is permeability of surrounding soil for horizontal consolidation, k_s is permeability of surrounding soil for horizontal consolidation in smeared zone, S is ratio between equivalent diameter of smeared zone (d_s) and equivalent diameter of PVD (d_w).

$$F_r = \pi z(L - z) \frac{k_h}{q_w} = 0.001$$

($k_h = 0.0145$ m/year; $q_w = 1000$ m³/year)

where z is the distance from the drainage end of the PVD, L is the length of the PVD when drainage occurs at both ends, and q_w is the discharge capacity of the PVD. The coefficient μ was determined as 2.37, calculated from the empirical relationship $\mu = 2.09 + 0.28 + 0.001$, as proposed by Seah *et al.* (2004).

It is assumed that the coefficient of permeability of the smeared clay is similar to the vertical coefficient of permeability, giving to a low F_s value. For the third component, since the discharge capacity of the PVD is over 1000 m³/year at a hydraulic gradient of 1, the F_r value is therefore negligible. In summary, the μ value is dominated by the first component. The other two components make a small contribution to the computed horizontal coefficient of consolidation.

The coefficient of consolidations in horizontal drainage indicated in Tables 1 to 4 could be obtained from the equation (10).

6. The Asaoka method was then applied by constructing the prediction of settlement versus time curve as per the equation (11). From the equation, the settlement depends on the slope (β) and the selected time interval (Δt). The results of time settlement curves are shown in Figures. 4 to 7 for the various settlement plates.

1. Time intervals and time Periods using in Evaluation: Tables 1 to 3 and Figures 4 to 7 show that the shorter time period (6 months after final surcharge loading) would yield the lower ultimate settlement, resulting in the higher degree of consolidation. It could be inferred that if an evaluation done too early after surcharge completion, this might lead to overestimation of consolidation degree of the soft Bangkok clay. The ultimate settlements ranged from 1.57 m to 2.00 m

Table 1. Asaoka method with various time intervals at 6 months after surcharge

Plate No.	Asaoka	7 days	14 days	21 days	28 days	42 days	56 days
SP-A1-059	S _{ult} (m)	1.631	1.635	1.643	1.659	1.638	1.674
	S _i (m)	1.410	1.410	1.410	1.410	1.410	1.410
	U _i %	86.4	86.3	85.8	85.0	86.1	84.2
	c _h (m ² /yr)	1.00	0.99	0.97	0.94	0.99	0.91
SP-A2-018	S _{ult} (m)	1.733	1.808	1.800	1.805	1.824	1.897
	S _i (m)	1.502	1.502	1.502	1.502	1.502	1.502
	U _i %	86.7	83.1	83.5	83.2	82.3	79.2
	c _h (m ² /yr)	1.03	0.92	0.93	0.92	0.89	0.79
SP-A3-115	S _{ult} (m)	1.572	1.586	1.596	1.622	1.599	1.626
	S _i (m)	1.375	1.375	1.375	1.375	1.375	1.375
	U _i %	87.5	86.7	86.2	84.8	86.0	84.6
	c _h (m ² /yr)	1.04	1.01	1.00	0.94	0.99	0.93
SP-A4-040	S _{ult} (m)	1.805	1.793	1.794	1.781	1.802	1.802
	S _i (m)	1.600	1.600	1.600	1.600	1.600	1.600
	U _i %	88.6	89.2	89.2	89.9	88.8	88.8
	c _h (m ² /yr)	1.10	1.13	1.12	1.16	1.10	1.11

Table 2. Asaoka method with various time intervals at 9 months after surcharge

Plate No.	Asaoka	7 days	14 days	21 days	28 days	42 days	56 days
SP-A1-059	S _{ult} (m)	1.700	1.700	1.680	1.689	1.679	1.697
	S _i (m)	1.548	1.548	1.548	1.548	1.548	1.548
	U _i %	91.1	91.1	92.1	91.7	92.2	91.2
	c _h (m ² /yr)	0.89	0.88	0.91	0.89	0.92	0.88
SP-A2-018	S _{ult} (m)	1.817	1.822	1.819	1.821	1.828	1.853
	S _i (m)	1.656	1.656	1.656	1.656	1.656	1.656
	U _i %	91.1	90.9	91.1	90.9	90.6	89.4
	c _h (m ² /yr)	0.91	0.90	0.90	0.90	0.89	0.84
SP-A3-115	S _{ult} (m)	1.667	1.688	1.672	1.668	1.658	1.632
	S _i (m)	1.519	1.519	1.519	1.519	1.519	1.519
	U _i %	91.1	90.0	90.9	91.1	91.6	93.1
	c _h (m ² /yr)	0.88	0.85	0.88	0.87	0.90	0.92
SP-A4-040	S _{ult} (m)	1.898	1.923	1.895	1.889	1.900	1.882
	S _i (m)	1.736	1.736	1.736	1.736	1.736	1.736
	U _i %	91.5	90.3	91.6	91.9	91.3	92.3
	c _h (m ² /yr)	0.94	0.91	0.94	0.96	0.93	0.97

Table 3. Asaoka method with various time intervals at 12 months after surcharge

Plate No.	Asaoka	7 days	14 days	21 days	28 days	42 days	56 days
SP-A1-059	S _{ult} (m)	1.761	1.752	1.764	1.767	1.762	1.773
	S _i (m)	1.652	1.652	1.652	1.652	1.652	1.652
	U _i %	93.8	94.3	93.6	93.5	93.8	93.2
	c _h (m ² /yr)	0.79	0.80	0.78	0.78	0.79	0.77
SP-A2-018	S _{ult} (m)	1.892	1.886	1.891	1.872	1.878	1.894
	S _i (m)	1.774	1.774	1.774	1.774	1.774	1.774
	U _i %	93.8	94.1	93.8	94.7	94.5	93.7
	c _h (m ² /yr)	0.80	0.81	0.80	0.83	0.82	0.79
SP-A3-115	S _{ult} (m)	1.734	1.742	1.739	1.742	1.728	1.740
	S _i (m)	1.624	1.624	1.624	1.624	1.624	1.624
	U _i %	93.6	93.2	93.4	93.2	94.0	93.3
	c _h (m ² /yr)	0.79	0.77	0.78	0.76	0.80	0.77
SP-A4-040	S _{ult} (m)	2.007	2.002	2.004	1.998	2.000	2.007
	S _i (m)	1.911	1.911	1.911	1.911	1.911	1.911
	U _i %	95.2	95.5	95.4	95.6	95.6	95.2
	c _h (m ² /yr)	0.79	0.80	0.79	0.80	0.79	0.79

depending on the natural subsoil condition in each area. The ultimate settlements from the different time intervals from 7 days to 56 days were about the same values. Figures. 4 to 7 from the different time intervals from 7 days to 56 days were about the same values. Figures 4 to 7 illustrate that settlement versus time curves for each time interval are approximately identical. Thus, the ultimate settlement is independent of the selected time interval.

However, as shown in Figure 9 for a short time interval such as 7 days, the monitoring data points are not tally, that made it difficult to draw the trend line correctly unlike the plot using the data collected from a long time interval such as 42 days and 56 days. Therefore, it would need long monitoring period in order to collect sufficient data points for constructing the trend line.

As shown in Figures 4 to 7, the back analysis curves based on the Asaoka method are approximately agreed well with the monitoring

curves. As expected, the curve with longer monitoring period trends to be more coincided with the actual data. The curve using data at 12 months period in the solid line is the most consistent with the field curve following by the curves at 9 months and 6 months periods in the dotted and dashed lines, respectively, which are partly consistent. It can be therefore assumed that the Asaoka method is proficient for simulating actual settlement curves.

2. Coefficient of consolidation in horizontal drainage:

The coefficient of consolidation in horizontal drainage is tabulated in Tables 1 to 3. The values are 0.76 to 1.16 m²/y which is closed to 0.73 to 0.91 m²/y obtained by CRS-R at final stress level for depth of 4 to 9 m in West runway from the previous research by Seah *et al.* (2004). Using the longer monitoring period, the coefficient of consolidation in horizontal drainage shows the smaller value because of the steeper slope

of the fit curve according to equation (15). In addition, from the results, the coefficient of consolidation in horizontal drainage are independent of the selected interval times. It appears that the coefficient of consolidation in horizontal drainage generally depends on μ , the total sum of factors of PVD spacing, smear and well resistance effects.

Factors affecting evaluation by the Hyperbolic method

The same field settlement data as calculated previously were analyzed again based on the Hyperbolic method to examine the different factors affecting on the predictions of ultimate settlement and settlement versus time curve, degree of consolidation and coefficient of consolidation in horizontal drainage. The procedures were as follows;

1. T_{ri} was obtained from U_i at various degrees by using equation (14) with $\mu = 2.37$ as estimated previously, in the Asaoka method. Then, graph of T_{hi}/U_i versus T_{hi} was plotted as shown in Figure 10. The slope of the first linear segment (M) between U_{60} and U_{90} was determined by fitting curve with the linear regression (equation (12)) on this portion.

2. From settlement versus time curve, the graphs of t/s versus s with the various evaluation periods after surcharge placement were plotted as shown in Figure 11. The slope of the first linear segment (m) was estimated in the same way of M by using equation (15).

3. The settlement at the end of primary consolidation (S_{100}) was equal to M divided by m as shown in equation (17). The ultimate settlement can be calculated from S_{ult} (for the total surcharge stages) = $S_o + S_{100}$, where S_o was settlement before the final surcharge.

4. Then, the settlement at consolidation degree of 60% (S_{60}) was calculated by multiplying the ultimate settlement with 0.6. The time responding to S_{60} (t_{60}) was then found from the field settlement versus curve time. The coefficient of consolidation in horizontal drainage (c_h) was obtained by replacing t_{60} and T_{r60} into equation (13).

5. The prediction time versus settlement curve could then be constructed by replacing S_{ult} (for the final surcharge stage) = S_{100} from step 3, c_h from step 4 with $\mu = 2.37$ and $d_e = 1.13$ m as calculated formerly, into equation (5).

1. Time periods using in evaluation: The evaluation by the Hyperbolic method was carried out for the various areas at different periods of 6, 9 and 12 months after surcharge placement. Table 4 compares the magnitude of ultimate settlement, degree of consolidation and coefficient of

consolidation in horizontal drainage predicted by the Hyperbolic method. Figure 11 shows the Hyperbolic plots at evaluation periods of 6, 9 and 12 months after surcharge placement for the SP-A1-059.

The slope of Hyperbolic plot is slightly constant with the periods of evaluation. Thus, the predicted ultimate settlement is found to rather constant with the periods of evaluation as apparent in Table 4. Figures 4 to 7 indicate the prediction of settlement versus time curves by the Hyperbolic methods. The result shows that three curves at the different periods of evaluation are coincided with the field curves for all areas. Therefore, it can be expected that the Hyperbolic method could be also adopted for simulating actual settlement curves.

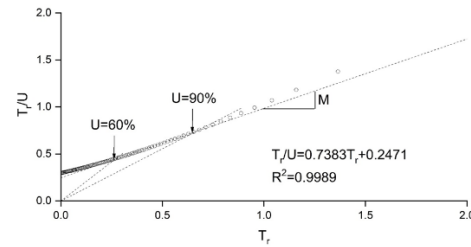


Figure 10. T_r/U versus T_r with $m = 2.37$

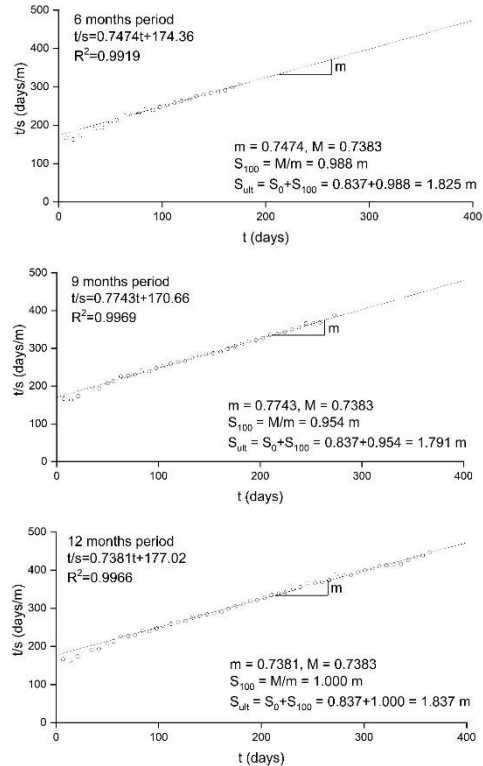


Figure 11. Hyperbolic plots at SP-A1-059 for the various periods of evaluation after preloading

2. Coefficient of consolidation in horizontal drainage: The coefficient of consolidation in horizontal drainage is tabulated in Table 4. The values are 0.55 to 0.75 m^2/y which is rather less than that of 0.76 to 1.16 m^2/y and 0.73 to 0.91 m^2/y by Asaoka method and CRS-R (Seah *et al.*, 2004), respectively. The values are approximately constant over the periods of 6, 9 and 12 months. It can be observed that the coefficient of consolidation in horizontal drainage by the Hyperbolic method is independent of the evaluation period.

Comparison between the Asaoka and Hyperbolic methods

The comparison of degree of consolidation between the Asaoka (28 days interval) and

Hyperbolic methods is summarized in Tables 5 to 7 for the evaluation periods of 6, 9 and 12 months after surcharge placement.

The ultimate settlement predicted by the Asaoka method is increasing with the longer periods of evaluation. Subsequently, consolidation degree estimated by the Asaoka method is decreasing with the longer periods of evaluation. The ultimate settlement predicted by the Hyperbolic method is almost constant over the various evaluation periods. The ultimate settlement and consolidation degree obtained by the two methods is found to reach the same value with each other as the evaluation period increases. The consolidation degree and the coefficient of horizontal consolidation estimated by the Hyperbolic method is found to be slightly lower than ones predicted by the Asaoka method.

Table 4. Hyperbolic method at 6, 9 and 12 months after surcharge

Plate No.	Hyperbolic	6 months	9 months	12 months
SP-A1-059	S_{ult} (m)	1.825	1.791	1.837
	S_i (m)	1.410	1.548	1.652
	$U_i\%$	77.3	86.5	89.9
	c_h (m^2/yr)	0.68	0.72	0.66
SP-A2-018	S_{ult} (m)	1.929	1.914	1.944
	S_i (m)	1.502	1.656	1.774
	$U_i\%$	77.9	86.5	91.3
	c_h (m^2/yr)	0.72	0.72	0.71
SP-A3-115	S_{ult} (m)	1.734	1.758	1.746
	S_i (m)	1.375	1.519	1.624
	$U_i\%$	79.3	86.4	93.0
	c_h (m^2/yr)	0.75	0.72	0.74
SP-A4-040	S_{ult} (m)	2.206	2.127	2.109
	S_i (m)	1.600	1.736	1.911
	$U_i\%$	72.5	81.6	90.6
	c_h (m^2/yr)	0.55	0.62	0.64

Table 5. Comparison of Asaoka of 28 days interval and Hyperbolic methods at 6 months after surcharge

Plate No.	Comparison	Asaoka	Hyperbolic
SP-A1-059	S_{ult} (m)	1.659	1.825
	S_i (m)	1.410	1.410
	$U_i\%$	85.0	77.3
	c_h (m^2/yr)	0.94	0.68
SP-A2-018	S_{ult} (m)	1.805	1.929
	S_i (m)	1.502	1.502
	$U_i\%$	83.2	77.9
	c_h (m^2/yr)	0.92	0.72
SP-A3-115	S_{ult} (m)	1.622	1.734
	S_i (m)	1.375	1.375
	$U_i\%$	84.8	79.3
	c_h (m^2/yr)	0.94	0.75
SP-A4-040	S_{ult} (m)	1.781	2.206
	S_i (m)	1.600	1.600
	$U_i\%$	89.9	72.5
	c_h (m^2/yr)	1.16	0.55

Conclusions and Recommendations

Based on the evaluation done on this study, it can be concluded and recommended as follows:

1. When a longer evaluation period was used in the prediction by the Asaoka method, the magnitude of ultimate settlement increased and the consolidation degree decreased.

2. The ultimate settlement and the consolidation degree predicted by the Asaoka method are independent of the selected time intervals.

3. The coefficient of consolidation in horizontal drainage back-analyzed by the Asaoka method is closed to that obtained from CRS-R at final stress level. It is independent of the selected time intervals and dependent on the evaluation periods. The values are lower with the longer evaluation periods.

4. It is recommended that for the Asaoka method, a longer time interval and a longer evaluation period are to be used for estimating the ultimate settlement and coefficient of consolidation in horizontal drainage predictions.

5. The ultimate settlement and the consolidation degree predicted by the Hyperbolic method are almost constant over the various evaluation periods and time intervals.

6. The coefficient of consolidation in horizontal drainage back-analyzed by the Hyperbolic method is independent of the selected time intervals and the evaluation periods.

7. The predictions of ultimate settlement and degree of consolidation from the Asaoka and Hyperbolic methods are found to be in good agreement especially when the evaluation period increases.

Table 6. Comparison of Asaoka of 28 days interval and Hyperbolic methods at 9 months after surcharge

Plate No.	Comparison	Asaoka	Hyperbolic
SP-A1-059	S_{ult} (m)	1.689	1.791
	S_i (m)	1.548	1.548
	$U_i\%$	91.7	86.5
	c_h (m ² /yr)	0.89	0.72
SP-A2-018	S_{ult} (m)	1.821	1.914
	S_i (m)	1.656	1.656
	$U_i\%$	90.9	86.5
	c_h (m ² /yr)	0.90	0.72
SP-A3-115	S_{ult} (m)	1.668	1.758
	S_i (m)	1.519	1.519
	$U_i\%$	91.1	86.4
	c_h (m ² /yr)	0.87	0.72
SP-A4-040	S_{ult} (m)	1.889	2.127
	S_i (m)	1.736	1.736
	$U_i\%$	91.9	81.6
	c_h (m ² /yr)	0.96	0.62

Table 7. Comparison of Asaoka of 28 days interval and Hyperbolic methods at 12 months after surcharge

Plate No.	Comparison	Asaoka	Hyperbolic
SP-A1-059	S_{ult} (m)	1.767	1.837
	S_i (m)	1.652	1.652
	$U_i\%$	93.500	89.900
	c_h (m ² /yr)	0.7800	0.660
SP-A2-018	S_{ult} (m)	1.872	1.944
	S_i (m)	1.774	1.774
	$U_i\%$	94.700	91.300
	c_h (m ² /yr)	0.830	0.710
SP-A3-115	S_{ult} (m)	1.742	1.746
	S_i (m)	1.624	1.624
	$U_i\%$	93.200	93.000
	c_h (m ² /yr)	0.760	0.740
SP-A4-040	S_{ult} (m)	1.998	2.109
	S_i (m)	1.911	1.911
	$U_i\%$	95.600	90.600
	c_h (m ² /yr)	0.800	0.640

8. The prediction of settlement versus time curves based on the Asaoka and Hyperbolic methods are revealed to be almost coincided with the field curves especially with the longer evaluation period. Thus, it is recommended that the prediction of settlement versus time curves by these two methods shall be adopted in practice due to their proficiency and simplicity.

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