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A Study on the Prediction of Long-Term Settlement by the Modified Hyperbolic Method

수정된 쌍곡선 법을 이용한 장기 침하량 예측

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요 지

최종침하 예측기법들은 분석상 간단명료하고 경제적인 기법이라 현장에서 널리 이용되고 있지만, 현장계측상의 문제들이 다분히 있는 실측치에 크게 의존함으로써 설계단계에서 침하량예측에 분석가의 주관적 판단이 큰 변수로 작용할 수 있으므로 객관성이 결여되는 결점을 안고 있다. 그 중 쌍곡선법(Hyperbolic Method)이 가장 널리 쓰이고 있지만, 현장 계측치에 따라 가정 기본식의 선형성이 다소 뚜렷하지 않아 분석가에 따라 해석결과가 다르게 나타날 수 있으므로, 기술 적용상의 어려움과 경제적 비용을 더욱 가중시키는 결과를 초래할 수 있다. 따라서, 본 연구에서는 현장 계측자료 분석에 있어서 대표적으로 널리 적용되고 있는 쌍곡선법의 기본 가정식의 선형성 문제에 주안점을 두어 기본 가정식의 선형성을 확보하고, 그 선형구간을 확장한 새로운 침하예측기법을 제안하였다.

성토완료 직후의 현장 자료를 배수재가 설치된 지역과 배수재가 설치되지 않은 지역으로 구분하여 최종 1차 압밀침하량, 수직압밀계수 등을 기존예측기법 및 현장계측자료와 비교 검토하여 제안된 침하예측기법의 적용성을 검증하였다.

Abstract

Because the prediction methods of ultimate primary settlement are analytically simple and economical, they are widely used in the field. But the results from these methods using field data with possible measurement errors can be influenced by the engineer's judgement.

The hyperbolic method, which is most widely used in the field, does not have clear linear relationships of variables in the hypothesis conditions and then it can cause technical problems and economical costs. Therefore, in this study, in order to secure the basic linear of hypothesis and to expand the linear range, the new settlement prediction method is proposed. From the comparison of values of settlements and of vertical consolidation coefficients predicted by proposed method and those obtained from other prediction methods as well as field data, the application and the limitation of the proposed method were analyzed. In this analysis, the field data were divided into the data of vertical drain and the data of non-vertical drain

Keywords : Hyperbolic method, Long-term settlement, Ultimate primary settlement

1. Introduction

Lately, because of economy development, the demand for available land is increasing. So, the trend is moving from the inland areas which have comparatively good conditions into the coastal areas. The coastal areas are generally composed of soft clays. If structures and embarkments are constructed on them without counterm-

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easures, a large consolidation settlement will occur for the long-term and it will cause damage to the structures and embankments. The prediction of settlement in the design step is technically and economically very important. This needs a prudent and detailed analysis. Recently, the precise field data is required to predict the long-term settlement of soft ground improved by many geotechnical techniques. Now, in the application to widely used vertical drain methods, as reliability of their effects and the results of analysis are still under verification, the application of the prediction of long-term settlement is considered to have an influence on developing the analysis ability. Although prediction methods play an important part in analysis, the results obtained from these methods using field data with measurement errors can be subjected to the engineer's judgement. The hyperbolic method among the prediction methods is most widely used in the field since this method is analytically simple and economical. However, this method does not have clear linear relationships of variables and then it can cause technical problems and economical costs.

In this study, focused on securing the linear of basic hypotheses and expanding the linear range, the applicability and the limitation of the proposed method are analyzed through comparing with the results obtained from other prediction methods as well as field data. In the hyperbolic method, the relationship between consolidation settlement and time is assumed to approach a hyperbolic curve. The proposed logδ method is based on hypothesis that the relationship of logδ (settlement) and t(time) has the hyperbolic form.

2. The New Prediction Method of Ultimate Primary Settlement - Log δ Method

2.1 Ultimate Primary Settlement

2.1.1 Basic Hypertheses

Although a hyperbolic method is easily understood and widely used for prediction of primary settlement, the linear of the range of U_{60} ~ U_{90} is not clear. So, in order to make an apparent linear relation and expand its linear range, supposing that the relation of log δ and t has the hyperbolic form. The log δ method is proposed as follows :

$$\delta = 0, \quad \text{when } t = 0 \tag{1}$$

$$\log \delta = \frac{t}{a + \beta t}, \quad \text{when } t \neq 0 \tag{2}$$

Hence,

$$\lim_{t \to \infty} \delta = 10^{\frac{1}{\beta}} \tag{3}$$

Thus, Eq.(2) can be presented as the linear as follows :

$$\frac{t}{\log \delta} = a + \beta t \tag{4}$$

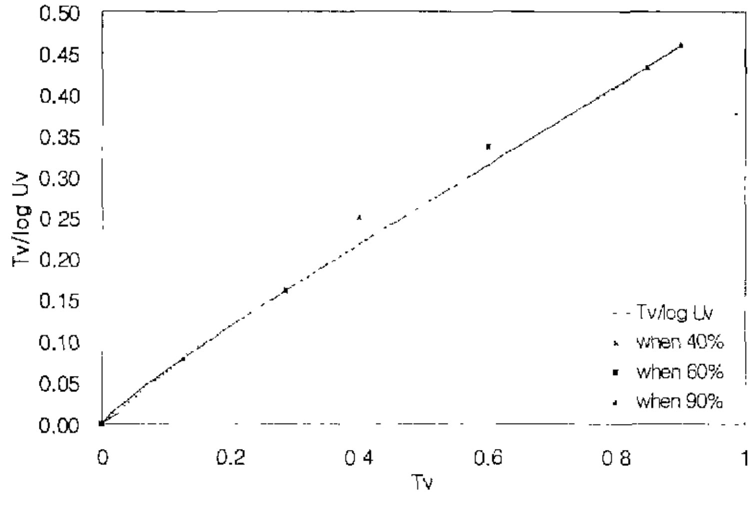

Fig. 1 $T_t/\log U_t$ vs T_t plot

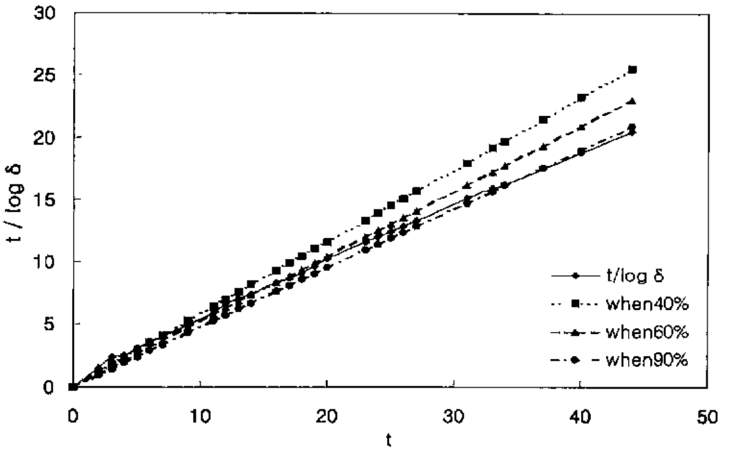

Fig. 2 t/log δ vs t plot by the field data

This means that the relation between t/log δ and t is the linear, with α as the intercept and β as the slope of the hyperbolic plot. Supposed that the ultimate primary settlement(δ_f) is reached when t = ∞, its value is $10^{\frac{1}{\beta}}$ as the exponential function.

But, Tan(1993) has pointed out that the inverse slope method overestimates ultimate settlement. This method is less useful for the field monitoring application. In this study, on behalf of the inverse slope method, the method proposed by Tan(1993) is followed.

2.1.2 Consolidation with Surcharge Only

The log δ method gives a unique settlement-time plot in terms of T_v(nondimensional time factor) against the U_v (average degree of consolidation). When the settlement is plotted as $T_v/\log U_v$ vs T_v as shown in Figure 1, the slope of linear segment between the U_{40} and U_{90} points is determined from a least square linear regression with coefficient of determination R^2 greater than 0.9999. This means that the segment between the U_{40} and U_{90} points of the theoretical $T_v/\log U_v$ vs T_v plot is the linear. This straight line portion can be represented by the equation :

$$\frac{T_v}{\log U_v} = \alpha_i \cdot T_v + C = 0.4886\ T_v + 0.0206 \quad (5)$$

where the α_i is the slope and C is the intercept of hyperbolic plot. When lines radiating from the origin are drawn to U_{40}, U_{60}, and U_{90}, the slopes of these lines are α_{40}= 0.6242, α_{60}= 0.5624, and α_{90}= 0.5117, respectively.

When a field settlement data is plotted in the form of t/log δ vs t as shown in Figure 2, the same features as the theoretical plot are observed. In this study, the unit of settlement (δ) and consolidation degree (U_v) is millimeter (mm) and percent(%). If the slope of initial linear segment (S_i) of the field data between U_{40} and U_{90} can be determined, the settlements can be calculated by constructing radiating lines to intersect the first linear segment of t/log δ vs t plot. Therefore, without a secondary consolidation, theoretically, the ultimate primary settlement can be presented as $\delta_{40}/0.4$, $\delta_{60}/0.6$, and $\delta_{90}/0.9$, respectively.

The slopes of lines radiating from the origin to U_{40}, U_{60}, and U_{90} on the t/log δ vs t plot are as follows :

$$S_{40} = \alpha_{40} \cdot \frac{S_i}{\alpha_i} = 0.6242 \cdot \frac{S_i}{\alpha_i} \quad (6)$$

$$S_{60} = \alpha_{60} \cdot \frac{S_i}{\alpha_i} = 0.5624 \cdot \frac{S_i}{\alpha_i} \quad (7)$$

$$S_{90} = \alpha_{90} \cdot \frac{S_i}{\alpha_i} = 0.5117 \cdot \frac{S_i}{\alpha_i} \quad (8)$$

where S_i is the initial slope of t/log δ - t vs t plot between U_{40} and U_{90}.

At the intersection of these radiating lines with the field plot, time and settlement for specific degree of consolidation can be obtained. Thus, the ultimate primary settlement is expressed as follows :

$$\delta_f = \frac{\delta_{40}}{0.4} = \frac{\delta_{60}}{0.6} = \frac{\delta_{90}}{0.9} \tag{9}$$

2.1.3 Consolidation with Vertical Drains and Surcharge

In this case, as the initial linear segment between the 40% and 90% consolidation stages is dependent on drain spacing ratio(n), the horizontal to vertical consolidation coefficient(c_h/c_v), and the vertical to horizontal drainage path length ratio(H/ d_e), the ultimate primary settlement can be calculated by Tan(1996)'s proposal considering both the vertical and the radial drainage. Tan(1996) applied Barron's theory for radial consolidation and Carrillo(1942)'s theorem for combined vertical(Terzaghi) and radial(Barron) flow to produce the theoretical settlement vs time data. The average degree of consolidation as a function of time factor for Terzaghi's theory of consolidation by vertical flow can be expressed as :

$$\text{when } Tv = \frac{c_v\, t}{H^2} < 0.2, \quad U_v = \sqrt{\frac{4T_v}{\pi}} \tag{10}$$

when

$$Tv = \frac{c_v\, t}{H^2} \geq 0.2\,, \quad U_v = 1 - \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 T_v}{4}\right) \tag{11}$$

The consolidation process in soils of low permeability by vertical drains is described by Barron(1948)'s theory. According to Hansbo(1981), without smear and well resistance effects, the ideal drain can be expressed as follows :

$$U_h(t) = 1 - \exp\left(\frac{-8T_h}{\mu}\right) \text{ where, } T_h = \frac{c_h\, t}{d_e^2} \tag{12}$$

$$\mu = \frac{n^2}{n^2-1}\ln(n) - \frac{(3n^2-1)}{4n^2} \tag{13}$$

where, n : drain spacing ratio(d_e/d_w)

d_e : diameter of an equivalent soil cylinder influenced by each drain

d_w : diameter of sand drain or equivalent diameter of prefabricated flexible drain

The values of d_e are equal to 1.13s for a square pattern and 1.05s for a triangular pattern(s = drain spacing). Hansbo(1981) recommended that $d_w = 2(w+b)/\pi$ for equivalent diameter of prefabricated flexible drain. The w is width of drain and b is thickness of the drain.

The average degree for combined vertical and radial consolidation was proposed by Carrillo(1942) as :

$$U = 1 - (1 - U_v)(1 - U_h) \tag{14}$$

Thus, after the theoretical $T_v/\log U$ vs T_v plot is drawn by the steps of the previous case of consolidation with surcharge only, the ultimate primary settlement(δ_f) of this case can be calculated using same procedure presented in the case of consolidation with surcharge only.

$$\delta_f = \frac{\delta_{40}}{0.4} = \frac{\delta_{60}}{0.6} = \frac{\delta_{90}}{0.9} \tag{15}$$

2.2 Consolidation Coefficient

2.2.1 Vertical Consolidation Coefficient(c_v)

Using the solution of the Terzaghi's theory, vertical consolidation coefficient is induced below. The slope of the linear segment of between the U_{40} and U_{90} points of the theoretical $T_v/\log U_v$ vs. T_v plot is a_i and the apparent intercept of this plot is C as follows :

$$\frac{T_v}{\log U_v} = a_i \cdot T_v + C = 0.4886\ T_v + 0.0206 \tag{16}$$

When the slope of line radiating from the origin drawn to any degree of consolidation $\left(\frac{a_d}{a_i} = A\right)$, as follows :

$$\frac{T_v}{\log U_v} = a_d \cdot T_v \text{ or } \frac{1}{\log U_v} = a_d \qquad (17)$$

Thus,

$$A = \frac{1}{a_i \cdot \log U_v} \qquad (18)$$

Using the data of the field with surcharge only, the linear equation is given below :

$$\frac{t}{\log \delta} = S_i \cdot t + c \qquad (19)$$

where δ is settlement(mm), t is settlement times(days), S_i is slope of the initial linear of U_{40} to U_{90}, and c is intercept.

When $\frac{a_d}{a_i} = \frac{S_d}{S_i}$, the linear radiating from the origin to any point of $U_{40} \sim U_{90}$ is expressed as :

$$\frac{t}{\log \delta} = S_d \cdot t = \frac{a_d}{a_i} \cdot S_i \cdot t = A \cdot S_i \cdot t \qquad (20)$$

Combining Eq.(19) and Eq.(20), the times can be obtained as :

$$t = \frac{c}{(A-1) \cdot S_i} \qquad (21)$$

By a function of time factor for Terzaghi's theory, the vertical consolidation coefficient(c_v) is given as :

$$c_v = \frac{T_v \cdot H^2}{t} = \frac{T_v(A-1) \cdot S_i \cdot H^2}{c} \qquad (22)$$

Thus, when $A-1 = \frac{c}{t \cdot S_i} = \frac{C}{T_v \cdot a_i}$, the vertical consolidation coefficient(c_v) is arranged as :

$$c_v = \frac{C}{a_i} \cdot \frac{S_i H^2}{c} = 0.0422 \cdot \frac{S_i H^2}{c} \qquad (23)$$

2.2.2 Horizontal Consolidation Coefficient(c_h)

According to the theory proposed by Tan(1996), when the times for 40%, 60%, and 90% consolidation (t_{40}, t_{60}, t_{90}) in vertical drain system and the value of c_v from laboratory oedometer tests on high quality undisturbed field samples are known, average horizontal consolidation coefficient(c_h) in the field can be estimated. In the case of the vertical drain, U_v rarely exceeds 50%. By the times for 40%, 60%, and 90% consolidation(t_{40}, t_{60}, t_{90}), U_v can be calculated from Eq.(10).

The average degree of consolidation for t_{40}, t_{60}, and t_{90} is 0.4, 0.6, and 0.9, respectively. With Eq.(14), U_h can be calculated. Thus, rearranging Eq.(12), c_h is given as :

$$c_h = \frac{-\mu d_e^2 \ln(1-U_h)}{8t} \qquad (24)$$

3. Application to the Field

3.1 The Case of Consolidation with Surcharge Only

The concerned area of this study was reclaimed for the construction of the housing development complex of which the total land is 2,185,000 m^2. With the data observations finished, two locations of instruments (GS-101, GS-102) by surcharge only in this area was analyzed. The area located in soft clay area was composed of surcharge, sedimentary soil layer, weathering residual layer, and weathering rock layer. Surcharge layer of about 4.6 to 6.5 m of sandy gravels and general soils was placed on the origin ground and sedimentary soil layer to improve consisted of the silty clays, and below it, weathering residual layer consisted of the silty sands into which the intact rock completely weathered, and there was rock layer under weathering.

In Fig. 3, the concerned layer was considered as the value of N between 0～6 and analyzed by each method.

In the Table 1 as well as Figure 4, for the case of the non-vertical drains, errors of the log δ method have the range of about 0～14%, and those of the hyperbolic

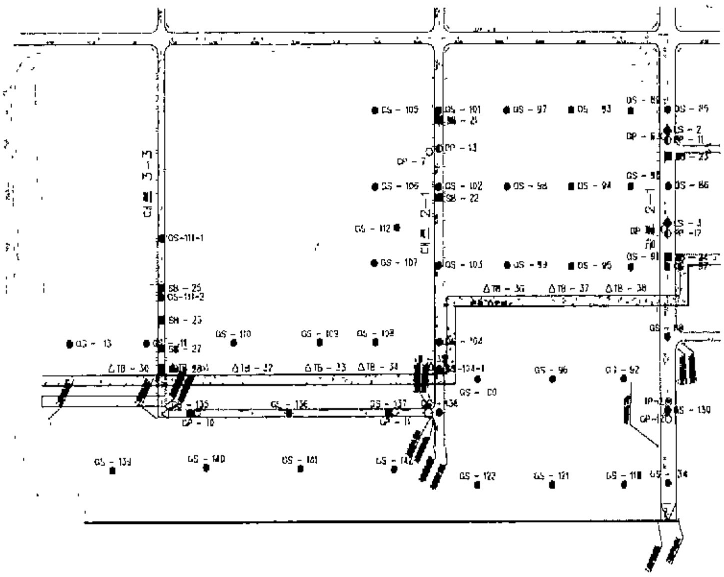

Fig. 3 Locations of gauges

method have the range of about 1 ~ 15%, and with time interval of 10 days, Asaoka method is mostly inclined to underestimate the ultimate primary settlement. But, in the GS-101, the hyperbolic method cannot predict settlements by means of U_{90}. Because line radiating from the origin does not cross any point on the t/δ $vs.$ t plot. It is considered that the uncertainty of the field data and the disregard of the vertical flow that has an important effect on the settlement cause these problems. Here, the Asaoka method is based on the fact that one dimensional consolidation settlements δ_0, δ_1, δ_2, etc. at times 0, Δt, 2 Δt, etc., can be expressed as a first order approximation by :

$$\delta_n = \beta_0 + \beta_1 \delta_{n-1} \tag{25}$$

which represents a straight line in a δ_{n-1} vs δ_n known as the Asaoka's plot, where β_0 is the intercept and β_1 is the slope of the line. When the ultimate primary settlement has been reached, $\delta_n = \delta_{n-1} = \delta_f$. Hence the end of primary or ultimate primary settlement δ_f is given by :

$$\delta_f = \frac{\beta_0}{1-\beta_1} \tag{26}$$

The coefficient of vertical consolidation(c_v) of Asaoka's method can be estimated by :

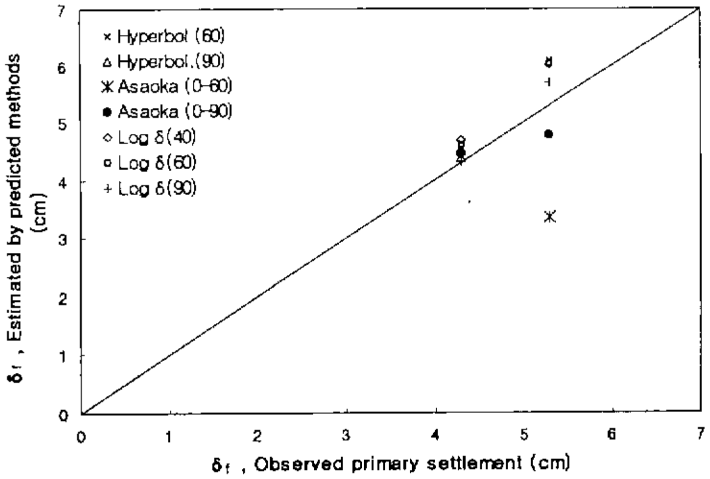

Fig. 4 Comparison of ultimate primary settlement by each method

Table 1. Ultimate primary settlement by the prediction methods

locations of instruments	ultimate primary settlement (cm)	log δ method			Hyperbolic method		Asaoka method	
		when 40% (cm)	when 60% (cm)	when 90% (cm)	when 60% (cm)	when 90% (cm)	when 0~60% (cm)	when 0~90% (cm)
GS-101	5.3	6.01	6 04	5.70	6 10	N/A	3.36	4.79
errors(%)		13.40	13.96	7 55	15.09	–	-36.6	-9.62
GS-102	4 3	4.68	4.60	4.32	4 47	4.39	N/A	4.45
errors(%)		8.84	6.98	0.47	3 96	2.09	–	3.49

Table 2. c_v by the prediction methods of settlement

locations of instruments	c_v in the laboratory (m^2/day)	log δ method (m^2/day)	Hyperbolic method (m^2/day)	Asaoka method (m^2/day)	
				0~60%	0~90%
GS-101	0 043459 to 0.10368	0.319741	0 3012	1 343911	0.7036650
GS-102		0.364007	0.404892	N/A	0.450062

$$c_v = -\frac{5}{12} \cdot \frac{H^2}{\Delta t} \cdot \ln\beta_1 \qquad (27)$$

where, H: drainage path

In the Table 2., for the case of the non-vertical drains, all the c_v of each method are overestimated 4~10 times those of the laboratory tests.

3.2 The Case of Consolidation with Vertical Drains and Surcharge

In the neighboring area of the western coast, it is difficult to secure sand for sand mat to improve a soft ground due to dredging reclamation. So, to estimate whether the dredged soil has ability for sand mat a small-scale construction test was carried out. The embankment materials of the construction test consisted of sand and dredged soil satisfying the appropriate conditions. The test area was divided into 4 Yards(Yard-1, Yard-2, Yard-4, Yard-6) for monitoring according to trench existence. As shown in Figure 5, the settlement plates, deep settlement gauge, piezometer, and ground water level gauge were installed to compare the improvement properties by the land conditions(Chun, et al. 1998).

In Fig. 5, the 3 Yards except for Yard-1 were analyzed to compare. The concerned areas of this study were composed of dredged reclamation layer and sedimentary soil layer. Dredged reclamation layer of about 3.2~4.5 m of silty sands and fine-grained sand was placed on the origin ground. The underlying sedimentary soil layer of about 6.5~10.3 m of the clayey silt and silty clay was irregularly distributed by each area. The sand drains of a square pattern were installed with their diameters(d_w) = 40cm, drain depth(H) = 6m, drain spacing(s) = 2.8m, and drain spacing ratio(n) = 7.91, assuming that c_h equals to c_v.

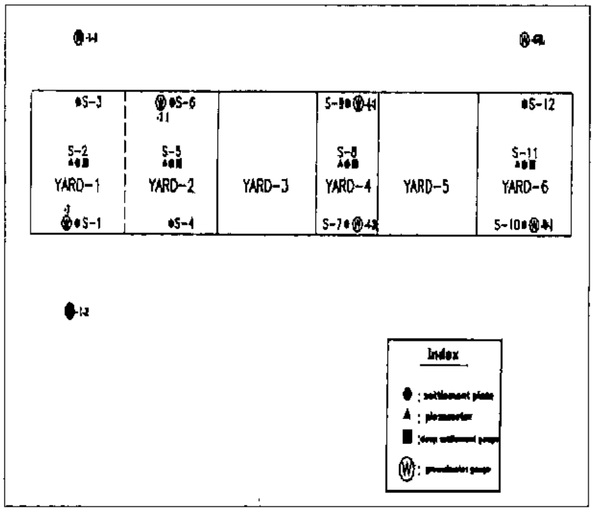

Fig. 5 Locations of gauges in the western coast test site

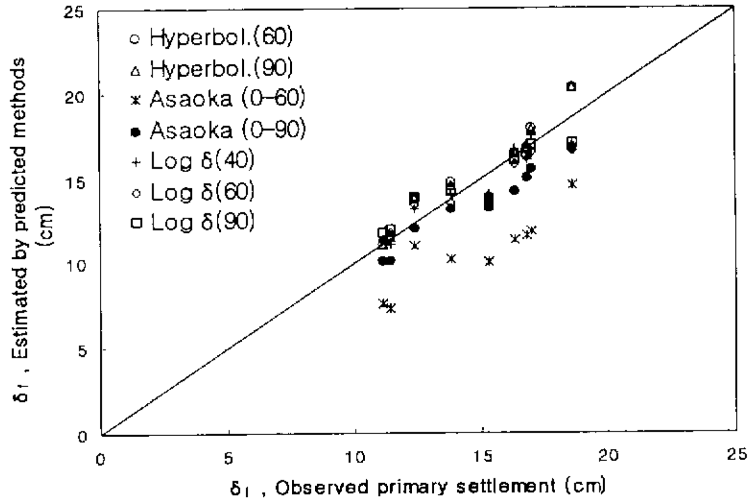

Fig 6 Comparison of ultimate primary settlement by each method

In the Table 3 as well as Figure 6, for log δ method, the errors of the ultimate settlement of about 0 ~ 13% were a little underestimated. Asaoka method, also, underestimated the ultimate settlement. For the hyperbolic method, the errors of about 1 ~ 12% were overestimated for those of log δ method. But, with the horizontal flow considered, it was possible to predict an accurate ultimate settlement for non-vertical drains. Using the results presented in Table 3, the ultimate primary settlements are plotted against the observed primary settlement in Figure 6 in order to compare the various estimates.

According to Table 4, all the c_v of each method are overestimated more than 10 times those of the laboratory tests because of representation problems of sampling for

Table 3. Ultimate primary settlement by the prediction methods

areas	locations of instruments	ultimate primary settlement (cm)	log δ method			Hyperbolic method		Asaoka method	
			when 40% (cm)	when 60% (cm)	when 90% (cm)	when 60% (cm)	when 90% (cm)	when 0~60% (cm)	when 0~90% (cm)
Yard-2	S-4	16.8	16.12	16.67	16.42	16.82	17.01	11.61	15.05
	errors(%)		4.05	0.77	2.26	0.12	1.25	-30.89	-10.42
	S-5	18.6	17.03	16.67	17.07	20.30	20.32	14.64	16.80
	errors(%)		8.44	10.38	8.23	9.14	9.25	-21.29	-9.68
	S-6	17.0	17.54	16.51	16.96	18.00	17.90	11.91	15.59
	errors(%)		3.18	2.88	0.24	5.88	5.29	-29.94	-8.29
Yard-4	S-7	11.1	11.37	11.35	11.83	11.05	11.08	7.57	10.08
	errors(%)		2.43	2.25	6.58	0.45	0.18	-31.80	-9.18
	S-8	12.4	13.22	13.48	13.93	13.81	13.83	11.03	12.07
	errors(%)		6.61	8.71	12.34	11.37	11.53	-16.57	-2.66
	S-9	11.4	11.13	11.79	11.98	11.62	11.54	7.27	10.14
	errors(%)		2.37	3.42	5.09	1.93	1.23	-36.23	-11.05
Yard-6	S-10	15.3	14.06	13.72	13.74	13.95	13.73	10.02	13.3
	errors(%)		8.10	10.33	10.20	8.82	10.26	-34.51	-13.07
	S-11	16.3	16.75	15.84	16.09	16.50	16.52	11.32	14.22
	errors(%)		2.76	2.82	1.29	1.23	1.35	-30.55	-12.76
	S-12	13.8	14.06	13.60	14.22	14.77	14.64	10.18	13.22
	errors(%)		1.88	1.45	3.04	7.03	6.09	-26.23	-4.20

Table 4. c_v by the prediction methods of settlement in the western coast area

areas	locations of instruments	c_v in the laboratory (m^2/day)	Hyperbolic method (m^2/day)	log δ method (m^2/day)	Asaoka method (m^2/day)	
					0~60%	0~90%
Yard-2	S-4	0.03404	0.39030	0.47928	2.77698	1.73650
	S-5		0.32802	0.46197	2.19602	1.71570
	S-6		0.32503	0.40077	2.18392	1.43183
	average	0.03404	0.34779	0.44734	2.38564	1.62801
Yard-4	S-7	0.04501	0.36910	0.27550	1.97019	1.26136
	S-8		0.28253	0.26278	1.34937	1.17244
	S-9		0.31210	0.27420	2.29635	1.31715
	average	0.04501	0.32124	0.27083	1.87197	1.25032
Yard-6	S-10	0.02519	0.41518	0.43388	2.38498	1.49077
	S-11		0.36197	0.42084	2.85661	1.83752
	S-12		0.25277	0.27682	1.56741	1.01975
	average	0.02519	0.34331	0.37718	2.26967	1.44935

the concerned areas, disturbance of the samples, the uncertainty of the laboratory tests, the shortage of the data of the consolidation tests in the field, and the effects of c_h/c_v.

4. Summary and Conclusions

In this study, in order to improve the linear problems in the hyperthesis conditions of the hyperbolic method to analyze consolidation properties of soft clay areas, a new settlement prediction method was proposed. From the comparison of values of settlements predicted by proposed method and those obtained from other prediction methods as well as field data, the applicability and the limitation of the proposed method are analyzed. The following conclusions can be drawn from the results reported herein :

1) The log δ method gives a unique settlement-time plot in terms of T_v(nondimensional time factor) against the U_v(average degree of consolidation). When the settlement is plotted as $T_v/\log U_v$ vs T_v, the slope of linear segment between the U_{40} and U_{90} points is determined from a least square linear regression with coefficient of determination R^2 greater than 0.9999.
2) In the t/δ *vs.* t plot, the slope of the linear segment of the log δ method between the U_{40} and U_{90} points has higher the value of R^2 than that of different methods between the U_{40} and U_{90}. This means that the linear segment of the log δ method is apparent linear and expanded.
3) Compared with the theoretical $T_v/\log U_v$ vs T_v plot, the case of consolidation with the vertical drains in the theoretical $T_v/\log U$ vs T_v plot has larger initial slope than that of consolidation without vertical drains.
4) In the prediction of settlement with the field data for the case of the non-vertical drains, errors of the log δ method have the range of about 0 ~ 14%, and those of the hyperbolic method have the range of about 1 ~ 15%. But, in the GS-101, the hyperbolic method cannot predict settlements by means of U_{90}. Because line radiating from the origin does not cross any point on the t/ δ vs t plot.
5) In the case of the vertical drains, for log δ method, the errors of the ultimate settlement of about 0 ~ 13% were a little underestimated. For the hyperbolic method, the errors of about 1 ~ 12% were overestimated for those of log δ method. But, with the horizontal flow considered, it was possible to predict an accurate ultimate settlement for

non-vertical drains. The prediction of non-vertical drains does not have the wide range of errors for vertical drains because of representation problems of sampling for the concerned areas, disturbance of the samples, the uncertainty of the laboratory tests, and, especially, the disregard of the vertical flow.

6) In the prediction of c_v with the field data, for the case of the non-vertical drains, all the c_v of each method are overestimated 4 ~ 10 times those of the laboratory tests. For the case of the vertical drains, all the c_v of each method are overestimated more than 10 times those of the laboratory tests because of representation problems of sampling for the concerned areas, disturbance of the samples, the uncertainty of the laboratory tests, the shortage of the data of the consolidation tests in the field, and the effects of c_h/c_v.

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