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Probabilistic method to determine the PBD installation space for soft ground Improvement

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ABSTRACT: Plastic board drain (PBD) method, one of soft ground improvement techniques, shorten drain path to accelerate consolidation process to improve shear strength of soft clay. The influence factors affecting to a degree of consolidation in PBD method are discharge capacity, smear zone, coefficient of consolidation, and surcharge loading et al. Until the present, however, deterministic methods in designing PBD method are unable to consider these factors and their uncertainties systematically. With quantitative analysis approach by statistics, it is possible to minimize errors occurred by uncertainties of influence factors in PBD design. In this paper, new probabilistic approach to overcome such issues in PBD design method has been discussed with case history. Thus, it is required to introduce a probabilistic analysis that allows this way to reflect on the outcome of consolidation analysis.

1 INTRODUCTION

Geotechnical engineering is more or less uncertain field compared to other civil engineering fields. Hence, a judgement of an engineer is very important. There were so many attempts to apply probability theoretical method to eliminate uncertainty for a decision of ground parameters. But it was inadequate. Consequently, confident design should be conducted through a combination of deterministic theoretical design method and probability theoretical design method. In case of PBD method for designing soft ground improvement, the degree of consolidation is mainly affected by ground condition, construction condition and the drain board characteristics. Such factors affecting the degree of consolidation are drainage capacity, smear zone, horizontal coefficient of permeability, and horizontal coefficient of consolidation and so on. However, because of insufficiency of data and uncertainty of input parameters, which are required to consolidation analysis of soft ground improvement, might be resulted in low reliability with designing such as underestimation or overestimation of consolidation process. Barron's method, Yoshikuni's method, Hansbo's method and Onoue's method (Onoue1988 are used for the degree of consolidation analysis in vertical drain method. These deterministic analysis methods assume that influence factors are constant values. However, since factors which affect settlement of ground and duration of consolidation are variable depending on test method applied and transformation model of design parameter, the deterministic design method may include uncertain values and unreliable results when designing soft ground improvement.

In deterministic method which is based on concept of safety factor, safety is judged by not variance but only the representative value. Therefore, it is not possible to take account of uncertainty of influence factors with existing PBD design. On the other hand, it is more reasonable to consider uncertainty from variance of ground parameters and artificial error for probability theoretical analysis method. In this study, the design process had been selected with assumption that the variable is ranged between constant values for analysis of ground consolidation behaviour by using probability theoretical method. Since ground parameters which affect settlement of ground and duration of consolidation are distributed according to the characteristics of variance, existing design methods have the problem that ground parameters are regarded as the fixed constant value. Investigated ground parameters had been statistically analyzed considering design parameters, which affect vertical drain method design. In addition, various design parameters investigated using probability theoretical simulation method for more reasonable vertical drain design method.

2 RELIABILITY ANALYSIS THEORY

2.1 Concept of reliability

In existing deterministic method for provision against uncertainty, it is commonly assumed that there is no failure due to an empirical excessive safety factor. However, sometimes failures are happened actually. On the other hand, the estimation of safety in engineering problem conducted with considering failure probability in reliability theory, which considers uncertainty quantitatively. The design according to reliability theory is composed of three levels. In the first level, the safety evaluation is conducted with determination of safety factor and the determined value which considered the coefficient of variation of each variable. It is possible to avoid the excessive design by using these methods. The first level method had been already introduced to design code. In the case of ISO(International Organization for Standardization), the design method of the level 1 had been established as the basis of structures design method. In the second level, it is confirmed whether the reliability index which is safety indicator from the average and the standard deviation of the load exceed the target value or not. In other words, the reliability index itself is the evaluation standard. The last third level is the method for more accurate evaluation of failure probability which the critical state equation is less than zero. The important thing for reliability analysis method is the reliability index (β). The design criterion Z which makes possible to judge safety and failure of structure is expressed by the load factor S and the resistance factor of structure R. The reliability index is expressed that the distance from the mean of probability function(Z) to the failure domain is normalized by the standard deviation(σ_z). And this is used for the index which represents the safety of system.

2.2 Monte Carlos Simulation (MCS)

The MCS is one of the most general methods which approximately presume failure probability. This method calculates failure probability by substitution sufficient amount of probability variables for the critical state equation. Merits of MCS are the failure probability can be calculated without any deformation of the critical state equation and the failure probability can be evaluated if only it is possible to judge whether it fails or not.

3 CONSOLIDATION BY VERTICAL DRAIN BOARD

3.1 Deterministic consolidation analysis

Vertical drain method makes consolidation finish in a short time and bearing capacity increase by using following two characteristics. The first characteristic is that the duration of clayey ground consolidation is directly proportional to square of drainage path length. The other characteristics is horizontal coefficient of permeability is bigger than vertical coefficient of permeability. Kjellman, Barron, Yoshikuni, Hansbo and Onoue's theories are the main focus of drain board installation study after Terzaghi's one-dimensional consolidation theory. The ground that drain boards are installed in shows radial consolidation. The Hansbo's equation(1) had been used for the consolidation analysis depending on installation space in this study.

$$F = F(n) + F(s) + F(w) \tag{1}$$

where,

$F(n)$ =Influence factor by drain board installation space

$F(s)$ =Influence factor by smear effect

$F(w)$ =Influence factor by drain resistance

3.2 Probability theoretical consolidation analysis

The type of drain boards and installation space should be determined for the attainment of the target degree of consolidation. But it is not certain whether the duration of consolidation from the deterministic analysis method is correct or not because of uncertainty of drain boards and ground. So the design method which is based on probability theory can be selected to solve those problems reasonably. If Ps is the probability of the degree of consolidation, it is possible to represent P_s as the equation (2).

$$P_s = P(U(t_s \geq U_s(t_s)) \tag{2}$$

where, $U(t_s)$ is the average value of the calculated degree of consolidation and t_s is the target degree of consolidation. The probability of the target degree of consolidation is a function of influence factors. So those influence factors should be noticed for the probability theoretical analysis. However, it is considered that each factors change randomly in some ranges because the exact distribution of each factor never been known. These influence factors can be represented by using statistical variables such as average, standard deviation and coefficient of variation which is normalized by average and standard deviation. The distribution of time-degree of consolidation depending on installation space can be obtained by distribution characteristics of those influence factors. And it makes possible to get the target degree of consolidation at a given time. In other words, the probability theoretical analysis is the method to evaluate the reliability depending on installation space of vertical drain boards, which satisfy the target degree of consolidation at a given time with considering statistical parameters of influence factors.

4 DESIGN OF VERTICAL DRAIN BOARD

4.1 Research area

In this study, Gwang-Yang area which is representative soft ground of Korea had been selected to conduct a test for factors that affect the degree of consolidation when the PDB method had been applied. Fig. 1 shows the applied area and Fig. 2 shows the representative cross section.

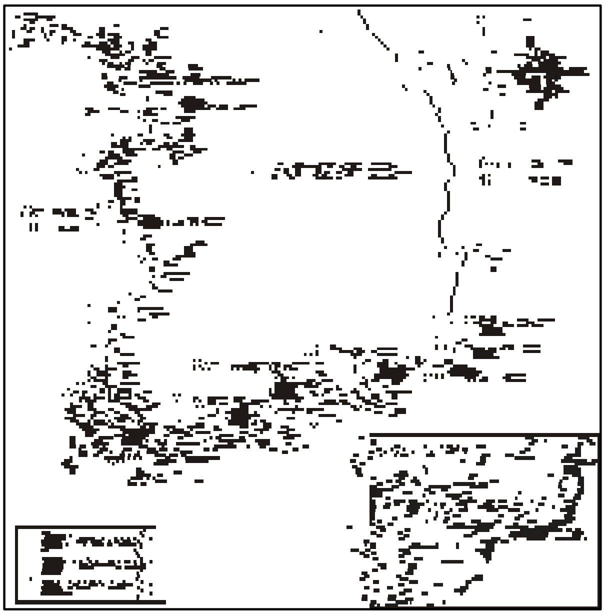

Fig. 1 Research area

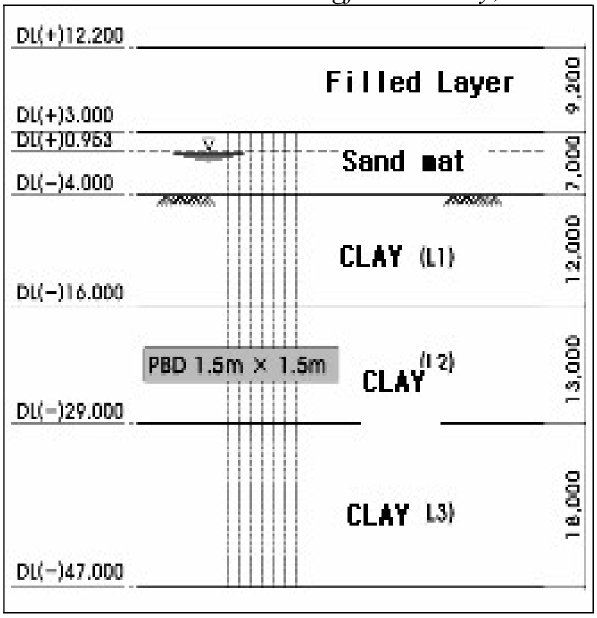

Fig. 2 Representative cross section

4.2 Reliability investigation condition

The place where occurred the biggest amount of settlement was selected as the representative cross section. And 90% of the target degree of consolidation had been determined during the improvement period at a loading step which had the biggest amount of settlement. The MCS analysis had been conducted for the consideration of ground's uncertainty. Design parameters related to consolidation such as the horizontal coefficient of consolidation had been attained through the MCS analysis, which affect mostly application of vertical drain method.

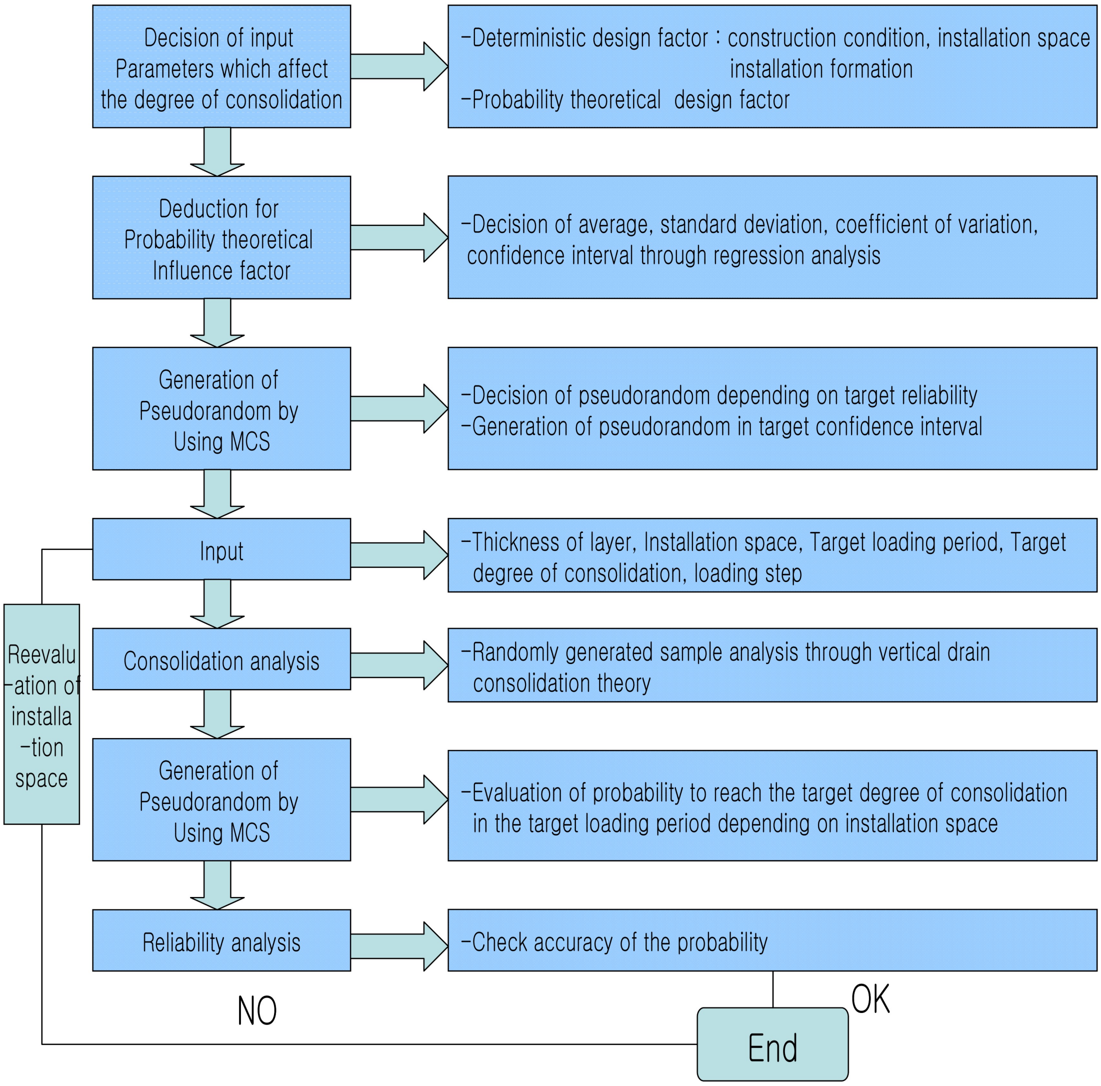

Fig. 3 Flow chart of reliability analysis

5 DRAIN BOARD DESIGN FACTOR

5.1 Introduction

The main design factors, which affect the degree of consolidation of soft ground, regarded as a probability theoretical design factor. Other factors, however, such as construction condition, installation space and installation formation were regarded as deterministic design factors in consolidation analysis. And it was analyzed that how much sensitive of design parameters to reach the target degree of consolidation depending on probability theoretical design factor. The dominant influence factor had been selected throughout their sensitivity analysis. And then, the suitability as input data were evaluated for probability theoretical analysis through equivalent statistical analysis of those design factors. Finally, the reliability of installation space of drain boards was analyzed. The probability distribution function is generally composed of Weibull distribution, lognormal distribution and Gaussian distribution. Weibull distribution is used for local generation of variables, index distribution for discontinuity analysis of earthquake or rock. Lognormal distribution is used for irregular distribution deformation which shows falling stones with different falling velocity. Gaussian distribution which is the most typical probability distribution had been used in this study. Fig. 3 shows a flow chart of those processes.

5.2 Sensitivity analysis

In the case of using vertical drain boards, the degree of consolidation is determined according to ground condition and the characteristics of a drain board. The difference between considering smear effect and well resistance and without those considerations, and understanding of the dominant influence factor of the degree of consolidation should be considered. The horizontal coefficient of consolidation, the horizontal coefficient of permeability, range of disturbed zone, the reduction ratio of the horizontal permeability coefficient and drainage capacity were selected as influence factors to analyze parameter sensitivity. Table 1 show the condition, which was used in sensitivity analysis.

Table 1. Sensitivity analysis conditions

Classification	Input variable	Unit	Applied value
Characteristic of Drain board	Width of Drain Board	*cm*	10
	Thickness of Drain Board	*cm*	0.4
	Converted Diameter (d_w)	*cm*	5.2
	Installation Space (S)	*cm*	100
	Arrangement Condition	-	Triangle
	Influence Circle(d_e)	*cm*	105
	Diameter of Mandrel (d_m)	*cm*	15
	Range of Disturbed Area (d_s)	*cm*	37.5
	Drainage Capacity(q_w)		5.0
Ground Condition	Horizontal Coefficient of Consolidation(c_h)	cm^2/sec	5.05E-04
	Horizontal Coefficient of Permeability(k_h)	cm/sec	7.40E-07
	Disturbed Horizontal Coefficient of Consolidation (k_s)	cm^2/sec	3.70E-07
Construction condition	Improvement Depth (L)	cm^2/sec	1000
	Improvement Period (t)	day	100

Fig. 4 to 8 show some results from sensitivity analysis, which represent the degree of consolidation with when each influence factor increase and decrease to 100% when other conditions are constant. In addition, Fig. 9 shows the range of the horizontal degree of consolidation depending on variation of influence factor.

According to Fig.s, the most dominant influence factors for consolidation analysis are the horizontal coefficient of permeability and that of consolidation. The second dominant influence factors are disturbed zone and reduction ratio of horizontal coefficient of permeability, which is related to smear effect. And the smallest influence factor is discharge capacity of drain boards. Hence, when PDB method is applied, the characteristics of horizontal consolidation for the ground should be calculated throughout more reliable test method not through application of standard consolidation test data to existing empirical formula. Because it has lower reliability in PDB method. In addition, if a discharge capacity is lower than 3.0, consolidation progress will be very slow. It will be sure that this delay of consolidation is same as the minimum of discharge capacity of vertical drain boards recommended by many researchers (Hansbo et al (1983)).

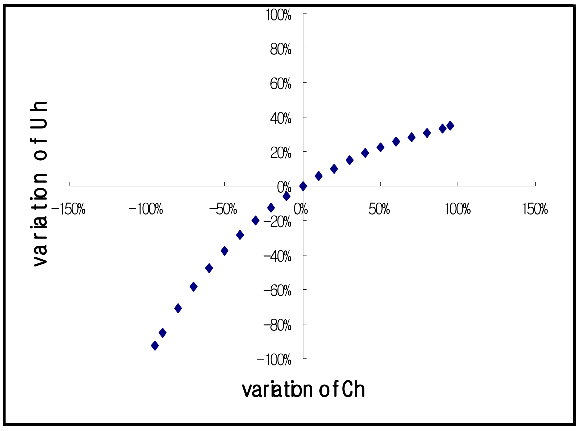

Fig. 4 Variation of U_h depending on C_h

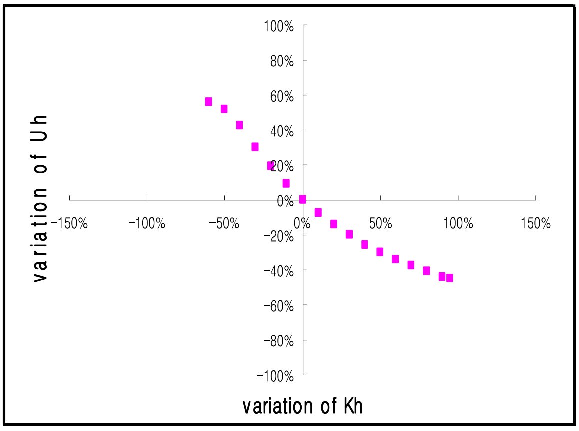

Fig. 5 Variation of U_h depending on k_h

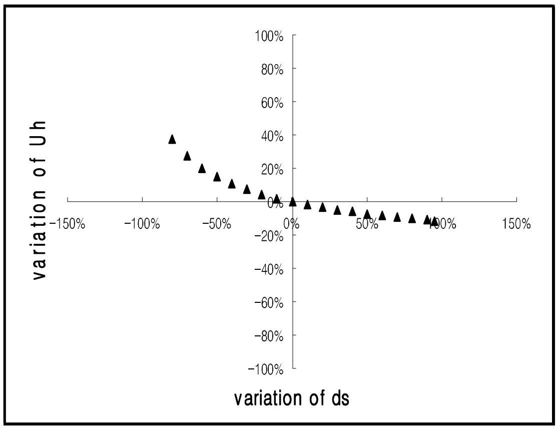

Fig. 6 Variation of Uh depending on ds

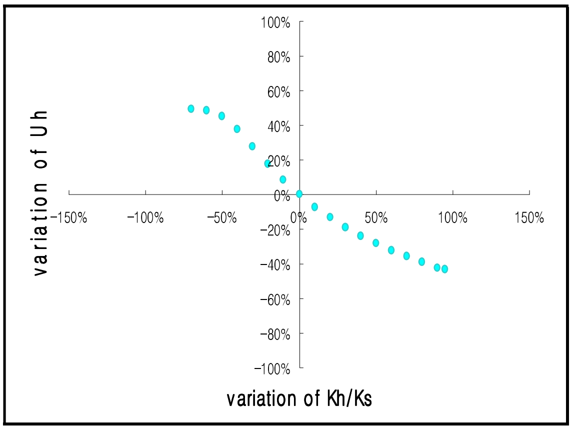

Fig. 7 Variation of Uh depending on kh/ks

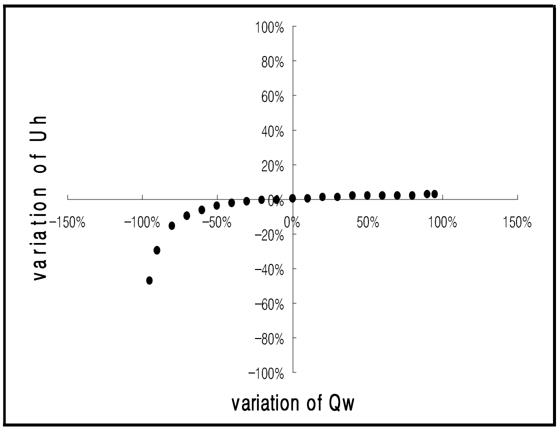

Fig. 8 Variation of Uh depending on Qw

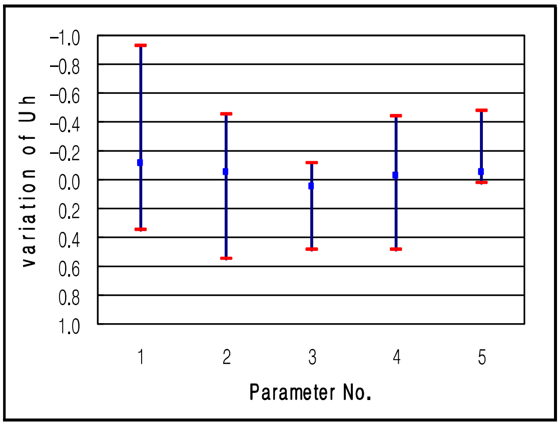

Fig. 9 Variation of Uh depending on the IF
(Notes ; 1 : c_h, 2: k_h, 3: d_s, 4: k_s/k_h, 5: q_w)

6 DECISION OF DRAIN BOARDS INSTALLATION SPACE

6.1 Analysis condition

The deterministic analysis conditions are 195 days of loading period, 90% of the degree of consolidation, doubled drain condition and tetragonal typed installation of drain boards, which are shown in table 2.

The probability theoretical analysis condition is the value for the consolidation characteristics of the ground and the influence factor. That value had been attained from test results for the researched area as mentioned previously. And in the case of construction of vertical drain boards to multilayered ground like the Fig. 2, equivalent coefficient of permeability, coefficient of consolidation and converted thickness of consolidation layer for the single layer had been calculated by using the coefficient of permeability and the coefficient of consolidation of the single layer. And consolidation analysis was conducted for the single layer with those values. The influence factor which is related to smear effect and well resistance had been applied by using values from medium sized consolidation and a discharge capacity test. Probability and statistical method had been used to minimize an error due to uncertainty of influence factors because influence factors estimated from tests include some uncertainties which could not disregarded when designing.

Table 2 Deterministic analysis conditions

Classification	Unit	Applied Value
Loading Period	day	190
Width of Drain Board	m	0.1
Thickness of Drain Board		0.004
Drainage Condition	-	Doubled Drain
Installation Formation	-	Tetragon
Target Degree of Consolidation	%	90
Target Probability	%	90, 95

Table 3 Representative values of influence factors for sensitive analysis

Classification		Unit	Average	Standard Deviation	Confidence Interval of Average	
					95% Upper Limit	95% Lower Limit
Vertical Coefficient of Consolidation	Dredged Ground	cm^2/sec	1.00E-03	3.00E-04	5.19E-04	4.81E-04
	Original Ground		5.00E-04			
Horizontal Coefficient of Consolidation	Dredged Ground	cm^2/sec	1.00E-03	8.52E-04	2.76E-03	2.66E-04
	Original Ground		2.71E-03			
Horizontal Coefficient of Permeability	Dredged Ground	cm/sec	1.00E-05	1.00E-07	1.86E-06	1.84E-06
	Original Ground		1.85E-06			
Discharge Capacity		cm^3/sec	4.00E-00	2.10E-01	4.01E-00	3.99E-00
S (d_e/d_w)		-	4.40E-00	2.30E-01	4.41E-00	4.39E-00
$\eta(k_h/k_s)$		-	3.00E-00	1.90E-01	3.01E-00	2.99E-00

6.2 Analysis results

Installation intervals are determined whether the target degree of consolidation is satisfied during loading period or not by using deterministic analysis method. On the other hand, consolidation analysis is conducted by using distribution characteristic of influence factors and a pseudorandom from average and standard deviation in the probability theoretical analysis method. The analysis data is expressed as a probability which satisfy the target degree of consolidation during a given loading period for each installation space. Fig. 10 shows a deterministic theoretical comparison between analysis data of average degree of consolidation depending on a time with considering both of smear effect and well resistance when drain boards installed completely. These data show same as Barron, Yoshikuni, Hansbo's horizontal drain theories. But it is judged that Onoue's theory calculates the degree of consolidation smaller because of considering consolidation delay bigger compared to other consolidation theories.

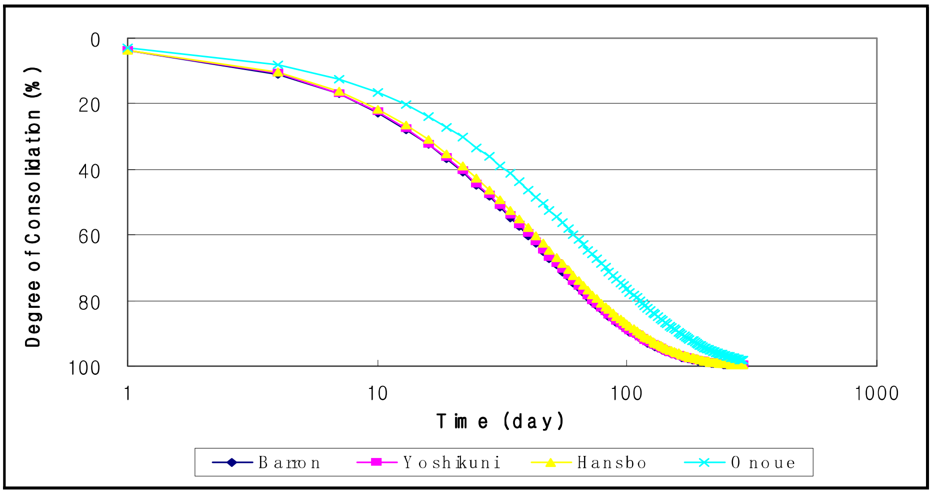

Fig. 10 Degree of consolidation with analysis method

Fig. 11 shows the degree of consolidation comparison when drain board installed completely and partially for the case of 1.2m installation space and 10m total ground layer. The degrees of consolidation for 190 day loading period were 93.29% for complete installation, 85.61% for 9.0m partial installation, 74.87% for 8.0m partial installation and 70.22% for 7.0m partial installation. The degree of consolidation for complete installation was bigger than those for partial installation. Therefore, partial installation of drain boards in the field due to an economic reason, pressure at the low ground can be the main cause of overestimation of the degree of consolidation.

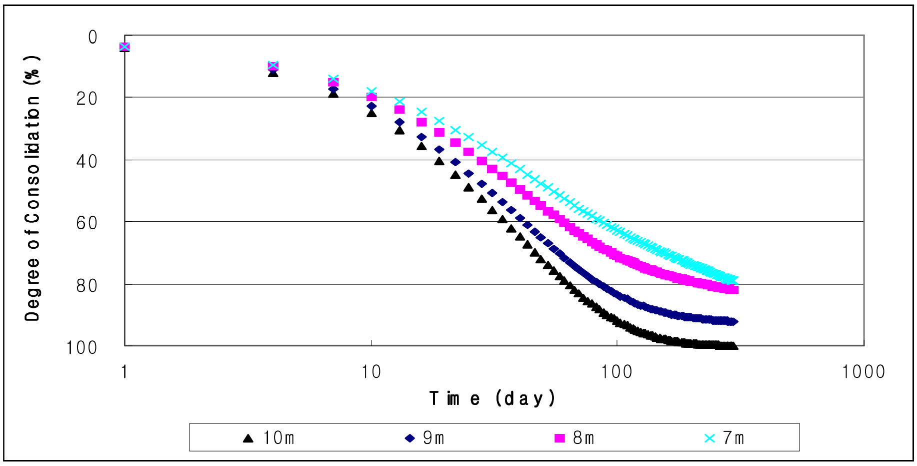

Fig. 11 Comparison between complete installation and partial installation with depth

Fig. 12 shows the analysis result comparison of time-average degree of consolidation depending on installation space from Hansbo's theory with considering smear effect and well resistance when drain boards had been installed completely. The degrees of consolidation for 190 day loading period were 97.83% for 1.0m installation space, 93.29% for 1.2m installation space and 83.24% for 1.5m installation space. In other words, 1.2m of installation space can be considered, which satisfy 90% of the target degree of consolidation during 190 day loading period by using average values of influence factors.

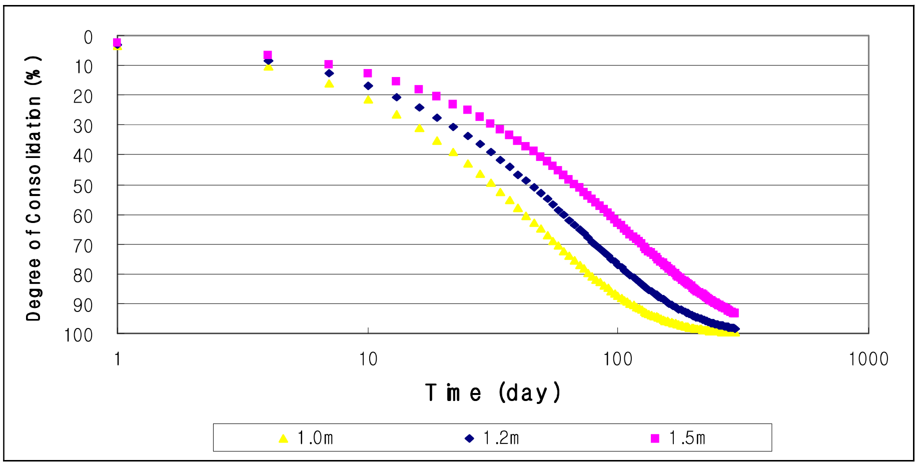

Fig. 12 Degree of consolidation with horizontal drain installation space

Fig. 13 shows analysis result of time-degree of consolidation comparison depending on installation space by using 95% upper limit average value of influence factors. The degrees of consolidation for 190 day loading period were 99.61% for 1.0m installation space, 97.96% for 1.2m installation space and 92.15% for 1.5m installation space. In other words, 1.5m of installation space can be applied, which satisfy 90% of the target degree of consolidation during 190 day loading period by using 95% upper limit average value of influence factors.

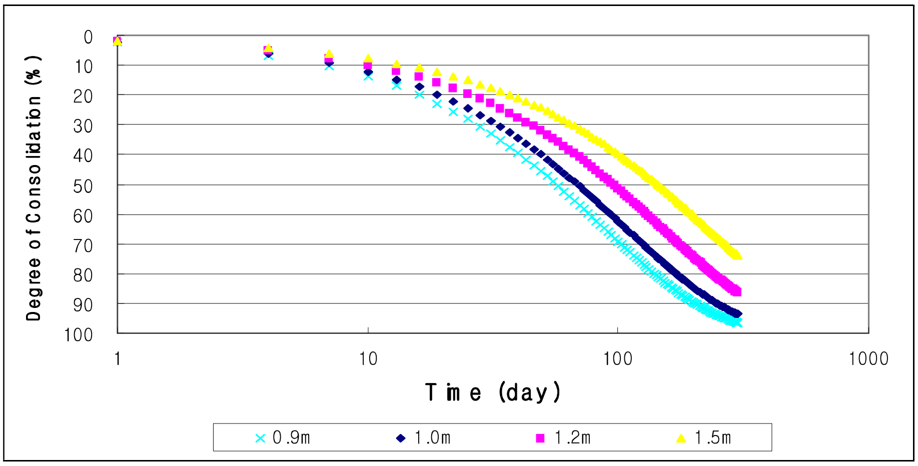

Fig. 13 Degree of consolidation with horizontal drain installation space

Fig. 14 shows analysis result of time-degree of consolidation comparison depending on installation space from Hansbo's theory with considering both of smear effect and well resistance by using 95% lower limit average value of influence factors. The degrees of consolidation for 190 day loading period were 90.05% for 0.9m installation space, 83.23% for 1.0m installation space, 72.55% for 1.2m installation space and 58.94% for 1.5m installation space. Hence, 0.9m of installation space can be gotten, which satisfy 90% of the target degree of consolidation during 190 day loading period by using 95% lower limit average value of influence factors.

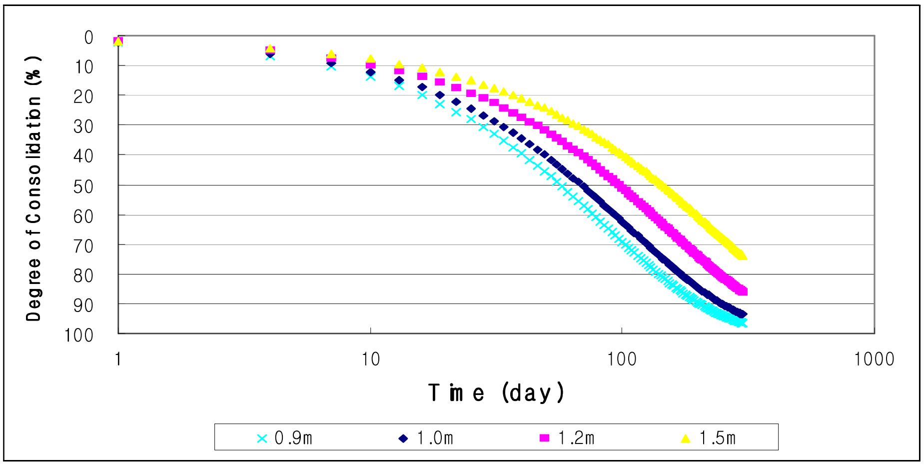

Fig. 14 Time-degree of consolidation with horizontal drain installation space

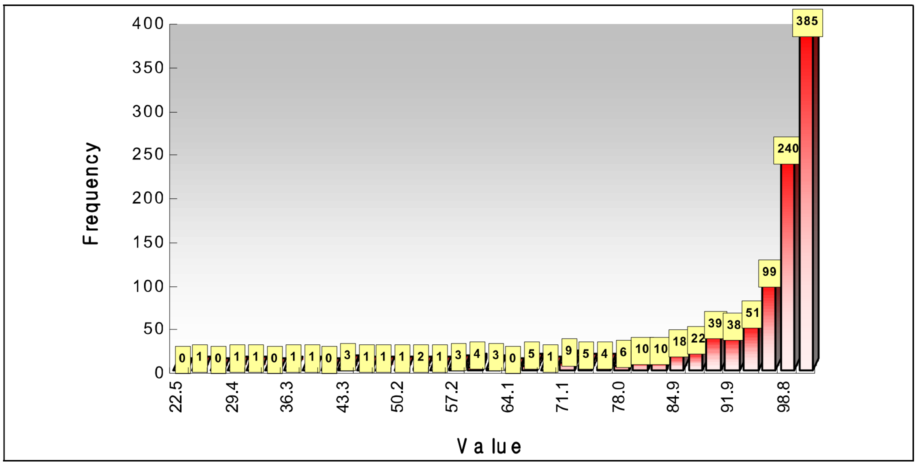

Fig. 15 Degree of consolidation distribution for 1.0m installation space

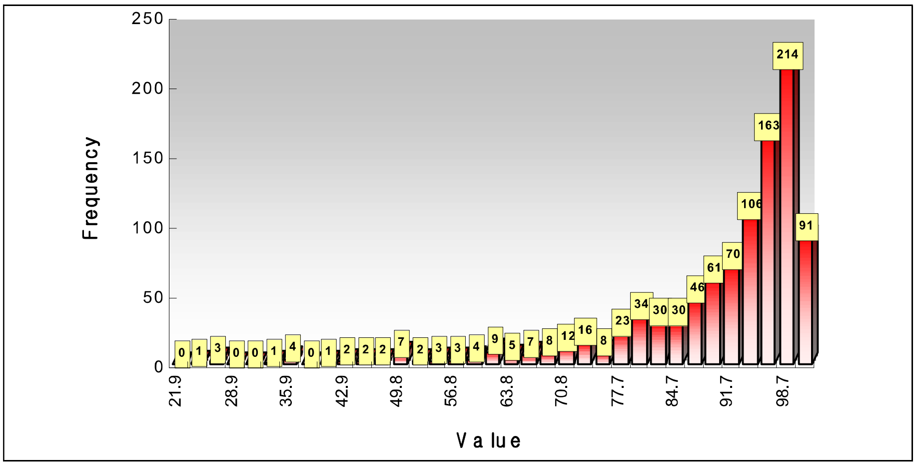

Fig. 16 Degree of consolidation distribution for 1.2m installation space

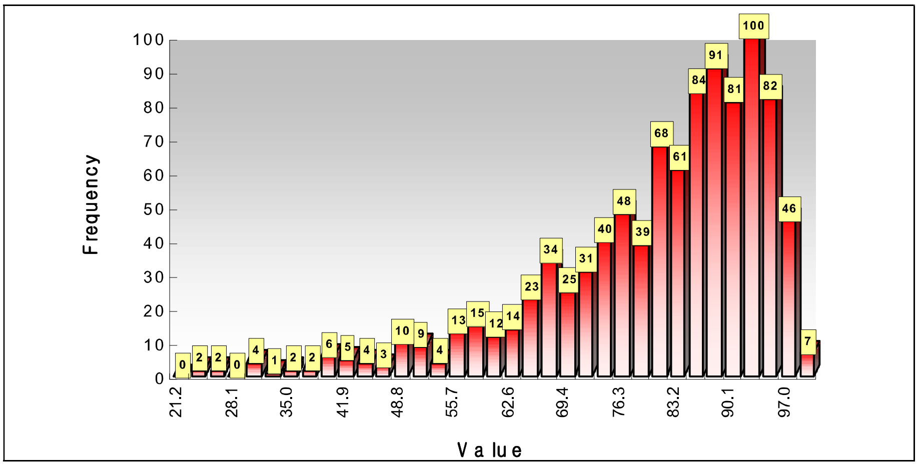

Fig. 17 Degree of consolidation distribution for 1.5m installation space

The single test had been conducted with 90%, 95% of confidence level. If the average degree of consolidation of the sample is bigger than the target degree of consolidation, it was regarded as a null hypothesis. And if not, it was regarded as an alternative hypothesis. Consequently, it can be judged that the target degree of consolidation can be satisfied with 1.2m installation space during a loading period as shown in Table 4.

Table 4. Test results for installation interval (target degree of consolidation=90%)

Installation Space	No. of Calculation	Average	Standard Deviation	Test Statistic	Confidence Level	
					90%	95%
1.0		94.49	9.72	14.908	Accept	Accept
1.2	1,000	90.85	11.95	2.249	Accept	Accept
1.5		79.85	13.62	-23.549	Reject	Reject

7 CONCLUSION

In this paper, Gwang-Yang area, which is representative soft, ground in Korea, following results have been obtained throughout sensitivity analysis on influence factors with probability method to decide drain board installation space reasonably.

As a result of sensitivity analysis for uncertain influence factors of vertical drain method, the dominant influence factor is the horizontal coefficient of consolidation. The second main influence factor is ratio of the horizontal coefficient of consolidation of undisturbed zone to that of disturbed zone. In order of a range of disturbed zone and a discharge capacity follow those influence factors.

As a result of consolidation analysis through deterministic theoretical analysis method for research area, installation space which satisfies the target degree of consolidation during a loading period depending on input condition of influence factors can be changed from 0.9m to 1.5m. Because test results for influence factors to the degree of consolidation and the suggested values by many researchers are not fixed values but changeable value which is uncertain. So, probability theoretical analysis method is necessary to minimize errors due to those uncertainties.

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