Proposal of Reasonable Fill Construction Management Index in Fill Loading with Vacuum Consolidation Method Based on FEM Analyses

by

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Vacuum consolidation method (VCM) is one of the recent methods for the improvement of soft ground. This method can forcibly drain pore water, and increase ground strength by loading of the vacuum pressure. A fill loading with vacuum consolidation method (FLVCM) is considered to be able to control lateral flow and upheaval of surrounding area during the rapid fill construction. However, the behavior of this combination on the ground deformation is not fully clarified on FLVCM, fill design and site management is depending on the experienced technique. In this study, numerical simulation has been carried out by finite element method (FEM) for the quantitative evaluation of the deformation suppression effect of FLVCM on the soft grounds of ariake clay, Japan. The utility of FLVCM was confirmed from comparison with the observed and the analytical ground deformation. In addition, the numerical simulation have been carried out under the various conditions of vacuum pre- and post-loading pressures and fill speeds, and it is suggested that the reasonable construction management index can be easily obtained by the site measurement of deformation.

Key words: *FEM, Lateral displacement, Settlement, Soft clay, Vacuum consolidation method*

1. INTRODUCTION

Japan is an eminent soft ground country also in the world. Recently, soft ground is widely spread, soft ground technology measures develop for soft clay and civil structures are often constructed because of the limited land area and over-population in the urban areas throughout the world. Therefore, a variety of soft ground improvement method have been developed and spread widely applied in the world.

The vacuum consolidation was first introduced by Kjellman5) to improve the strength of soft grounds and used to soft clayey deposits. In recent years, many successful field applications have been reported in the vacuum consolidation, including the use of vacuum preloading in a land reclamation project in china7),8). It is demonstrated the effectiveness of vacuum preloading consolidation in eliminating excessive settlement under static and dynamic loads on a airport runway11), 3) presented a successful case study whereby vacuum preloading was used to improve the soil strength at an oil storage station. Terzaghi's consolidation theory is revisited by vacuum and surcharge combined loading on the soft ground6). Especially in that case, vacuum consolidation is a soft grounds consolidation promotion method that applying vacuum pressure generates pore water pressure along the horizontal drain of the soil surface and along the length of a vertical drain installed in the soil, water and air has been exhausted compulsorily under the ground and increased soil strength, stability of the soft ground respectively, thereby reducing the time for attaining the ultimate ground settlement4). In other word, vacuum consolidation generally induces inner lateral displacement and can cause cracks in the surrounding surface area due to inward of the ground induced by application of the vacuum pressure 1) 2).

However, Many researchers have carried out their research work only on a particular vacuum consolidation

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method (VCM) while actually in the field quality and the type of fill consolidation constructions vary from pressure to pressure and fill speeds. This is attempted method that pore water drainage compulsorily, and increased ground strength by loading of the vacuum pressure. Rapidly fill construction and during the fill construction by control of lateral conception behavior and upheaval of surrounding area have been carried out on fill loading with vacuum consolidation method (FLVCM) that the fill construction and VCM is applied together measurement of the ground improvement. Therefore, in some cases, the combination of vacuum pressure and fill speed may provide well overall ground improvement. However, the ground deformation behavior is not clarified enough on FLVCM, and it has not arrived at a reasonable design method and site management is depending on the experienced technique.

In this study, numerical simulation has been executed by finite element method (FEM) that general fill construction, VCM, and FLVCM has been reproduced on the soft grounds of ariake clay, Japan. The utility of FLVCM was confirmed from comparison with the observed and the analytical ground deformation. In addition, the numerical simulation with the various vacuum pre- and post-loading pressures and fill speeds have been executed, and proposed a reasonable construction management index which can be easily obtain by the site measurements of ground deformation.

Table 1. Result of laboratory soil tests

Depth GL-m	Density ρ_s (g/cm^3)	Water content W (%)	Void ratio e	Degree of Saturation S_r (%)	Unconfined compressive strength q_u(kN/m^2)	Component (%)				Classification of soil
						Gravel	Sand	Silt	Clay	
2.00~2.90	2.609	147.1	3.816	100	21.1	0	1.5	36.2	62.3	Clay
3.00~3.90	2.639	136.3	3.585	100	26.5	0	9.6	33.7	56.7	Silt
4.00~4.90	2.663	107.2	2.875	99.2	28.3	0.2	36.4	26.9	36.5	
5.00~5.90	Sand layer, coefficient of permeability $k=1\times10^{-4}$cm/sec									Sand
6.00~6.90	2.627	119.2	3.132	100	45.1	0	5.7	40.8	53.5	Silt
7.00~7.90	2.641	125.7	3.318	100	38.5	0	2.5	39.9	57.6	
8.00~8.90	2.617	115.1	3.008	100	48.9	0	4.2	37.5	58.3	
9.00~9.90	2.656	116.5	3.008	100	44.1	0.1	1.9	35	63	Clay
10.00~10.90	2.684	90	2.444	98.9	64.7	0	10.3	37.5	52.5	Silt
11.00~11.90	2.647	67.4	1.782	100	60.7	0.2	11.2	32.8	55.8	

2. LABORATORY TESTING

The soil materials used in the present study were collected from ariake (undisturbed) in Saga prefecture, Japan. The physical properties in the samples were identified by laboratory soil tests. Table 1 shows the result of laboratory soil tests such as particle density, water content, void ratio, degree of saturation, unconfined compressive strength and composition of grain degree for the various depth soil samples on the soft ground respectively. The pore water pressure, settlement, lateral displacement in the soil samples were identified by triaxial vacuum consolidation test respectively. The detailed procedure is described by Tanabashi et. al.$^{10)}$.

3. NUMERICAL ANALYSIS OF FLVCM

3.1 Outline of analytical technique

In this analysis, sekiguchi-ohta model are applied as a soil behavioral model of soft clay behavior. Fill loading construction and VCM are reappeared by FEM analysis of the soil and water coupled. For express to the vacuum consolidation that the drainage boundary has been setting on the connected part of the vertical and horizontal drains. Moreover, the pore water pressure of the improvement area is compulsorily decreased with increasing of hydraulic head of the drainage boundary according to the loading vacuum pressure, and consolidation is to be advanced. When the vacuum pump was operated, vacuum pressure was given to top of the drain parts corresponded of the hydraulic head, and it was stopped, than condition of un-drain boundary was given.

3.2 Model analysis and input parameters

In this research, the plane strain condition was assumed, and the general boundaries as well as the 2D finite element

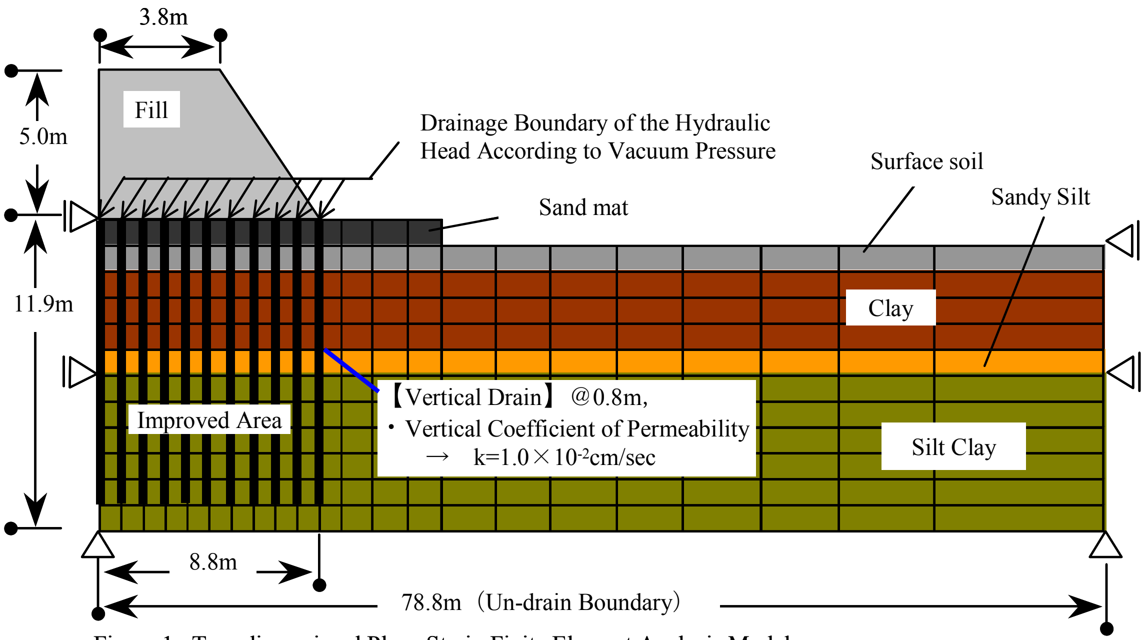

Figure 1. Two-dimensional Plane Strain Finite Element Analysis Model

method of a half section of the single improvement area (area 17.6m×187m, depth about 12m) that had been objected by the previous research$^{10)}$ in the field test constructed area shows the analysis model figure 1.

Table 2. Analytical model and input parameters

Name of layer		Depth (GL-m)	Model	φ (deg)	ν	Đ	Λ	M	K_0	k(cm/sec)
Fill		-	L.E	46.6	0.300	-	-	-	-	1.0×10^{-2}
Sand Mat		0.0~1.0		30.3	0.300	-	-	-	-	1.0×10^{-3}
Surface Soil		1.0~2.0	S.O	-	0.387	0.093	0.481	0.842	0.631	3.1×10^{-7}
Clay	1	2.0~3.0		-	0.387	0.133	0.480	0.840	0.631	3.1×10^{-7}
	2	3.0~4.0		-	0.378	0.088	0.514	0.900	0.608	2.9×10^{-7}
	3	4.0~5.0		-	0.361	0.092	0.579	1.013	0.566	2.5×10^{-7}
Sandy Silt		5.0~5.5	L.E	21.3	0.300	-	-	-	-	1.0×10^{-3}
Silty Clay	1	5.5~7.0	S.O	-	0.374	0.092	0.532	0.931	0.596	1.3×10^{-7}
	2	7.0~8.0		-	0.378	0.116	0.516	0.903	0.607	2.6×10^{-7}
	3	8.0~9.0		-	0.377	0.096	0.518	0.907	0.605	2.0×10^{-7}
	4	9.0~10.0		-	0.379	0.120	0.512	0.895	0.610	4.4×10^{-7}
	5	10.0~11.0		-	0.364	0.139	0.568	0.995	0.573	2.0×10^{-7}
	6	11.0~11.9		-	0.361	0.107	0.581	1.016	0.565	8.7×10^{-8}

Note: L.E.: Linear Elasticity, S.O.: Sekiguchi Ohta, φ: Friction Angle, υ: possion Ratio, Đ: Coefficient of Dilatancy, Λ: Nonreciprocal Ratio, M: Ratio of Limitation, K_0: Coefficient of Earth Rest, k: Vertical coefficient of permeability

It is necessary to put the vertical drain up to - 11.0m in depth at intervals of 0.8m respectively. The shape of the fill is assumed to be width 8.8m in the under, 3.8m in the area above, and fill height 5.0m respectively. Drainage boundary was setting on the head of the vertical drain according to the vacuum pressure. Moreover, table 2 shows the input analytical parameters. Surface soil, clay, and silty clay layer respected on sekiguchi-ohta model materials and fill, sand mat and sandy silt layer are respected on the linear elasticity behavior model as a shown material by modeled respectively. The indoor soil test results (table 1) of the sample collected from spot of the field test construction is used for the parameters setting.

3.3 Analytical cases

Table 3 shows construction method of analytical cases. There are three methods with compared to difference of deformation behavior of the ground such as fill construction method (FCM), VCM and FLVCM respectively. FCM and FLVCM have been assumed each of two cases according to the fill speed such as 20 cm/day and 50 cm/day respectively. Another a single case has assumed without fill construction respectively by VCM. Total five cases are executed in this analysis. It is assumed that fill construction has been setting on the fill height 5m, fill rest (vacuum pressure releases) 360 days respectively. Overall in this analysis applied –69kPa loading of vacuum pressure according to pore water pressure.

4. RESULTS AND DISCUSSION

4.1 Comparison with laboratory test and numerical analyses

Laboratory test and the numerical analysis of achievement field test construction are executed by using the above-mentioned physical properties of each layer, analytical model and the input parameters. In this paper, laboratory test samples and numerical analytical points are taken out of equal depth as GL-3.5m and GL-8.5m, respectively.

Figure 2 plotted for pore water pressure against elapsed time at various depths for the vacuum consolidation test. The data were recorded by laboratory test and model analyses according to 4.9m hydraulic head at depths of GL-3.5m and GL-8.0m respectively. There are approximately similar tendency of the pore water pressure in this figure. It is thought that the behavior of the pore water pressure can be caught from figure by the analysis and also the mechanism of the VCM in which it decreases in the pore water pressure because of action of the vacuum pressure is to be expressed by the analysis roughly. Moreover, it is put that an analytical value of hydraulic head (positive hydraulic head) has 3.5m given for the more similar to the actual field value, respectively.

Figure 3 shows relation ship between amount of ground settlement and elapsed time. From figure, 2.4m distant from the center of improvement area's model value are similar to actual field value but center of model value is larger than 2.4m distant from the center of the field value. Maximum settlement is the center according to the analytical result of the total improvement area. It is also thought that increased the distance from center with decreasing the amount of ground settlement.

Table 3. Analytical cases

Construction method	Fill Speed (cm/day)	Fill height (m)	Vacuum pressure	Period of vacuum pressure (day)
FCM	20	5	0	0
	50	5	0	0
VCFLM	20	5	-69	25
	50	5	-69	10
VCM	0	0	-69	25

Figure 4 shows the distribution depth of lateral displacement measured by field and model test. Lateral displacement has been showing in here 10.1m distant from center of the improvement area and this displacement is 98 days of elapsed time from starting of the construction. From figure, it has become small increased with increasing the hydraulic head of drainage boundary. In this analysis became a result that the difference with the field data extends into after and before correction of the hydraulic head but it is thought that the lateral shrinkage in the improvement area by the influence of vacuum consolidation is roughly express by the model.

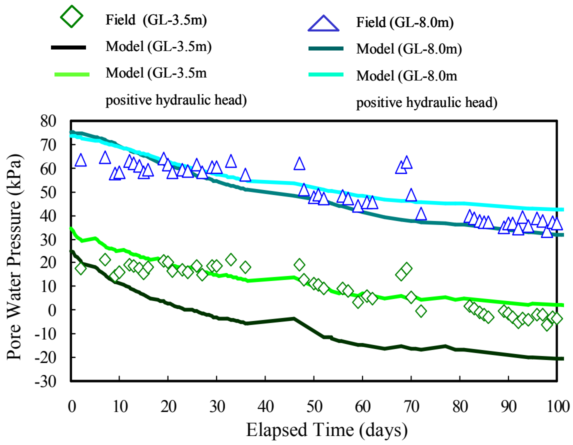

Figure 2. Plotted for the pore water pressure against elapsed time at various depths

Figure 2, 3 and 4 shows field with compare model test both are similar changing tendency in here. It is thought that assuming the model and soil parameters has been using appropriate, is discussed focus in terms of the relation of the model test to the settlement and lateral displacement,

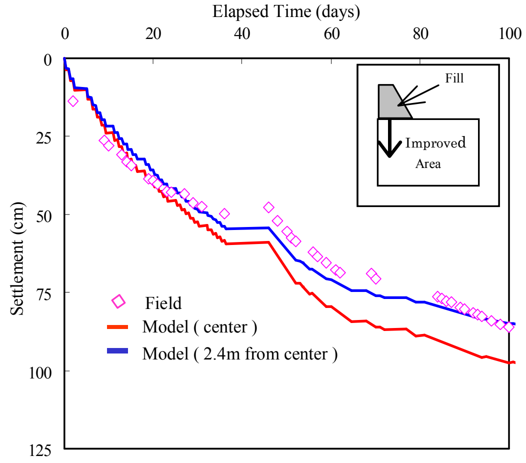

Figure 3. Relationship between amount of ground settlement and elapsed time

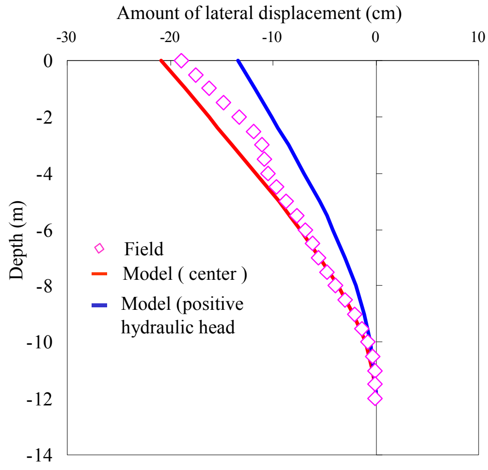

Figure 4. Plotted for the distribution depth of lateral displacement

and is indicated to be the overall index management accounting for the fill construction method in this analysis.

4.2 Numerical analyses

As follows, result discussion in here that there are two cases of the 20 cm/day fill speed such as FCM and FLVCM, another a single is VCM respectively. Those cases are compared with settlement behavior for the period of fill construction.

Figure 5 shows relationship between the amount of settlement and elapsed time at -4.0m depth center of the ground improvement area. In this figure, elapsed time 25days is filled active period and after 25days is called fill rest period. It is become result of maximum settlement due to loading of vacuum pressure according to the period of fill loading. It is thought that settlement behavior is excellent than influences of both parties of the loading of vacuum pressure and loading fill respectively. However, the FCM has become maximum settlement in the fill rest period, and rebound phenomenon has been generated in vacuum consolidation. It is thought that the residual settlement and the rebound behavior can be control superior by combination of FCM with VCM during the fill construction.

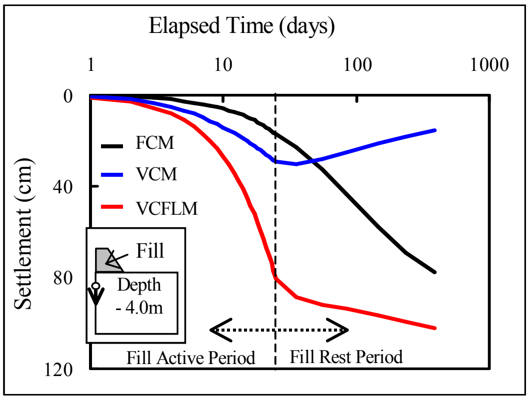

Figure 5. Plotted for amount of settlement VS elapsed time at 4.0m depth center of the improvement area

5. APPLICATION AND PROPOSAL OF CONSTRUCTION MANAGEMENT INDEX TO DEFORMATION BEHAVIOR

5.1 Amount of soil settlement and lateral flow

This is assumed for model ground of amount of soil settlement and lateral flow that it has been proposed the fill construction management index to understand the deformation behavior. Assumed for model ground of width and length are 10.1m and 11.9m respectively. Amount of soil settlement (V_S) and amount of soil lateral flow (V_δ) is calculated according to following equation

$$V_s = \Sigma \left\{ \frac{1}{2} \times (S_i + S_{i-1}) \times \Delta\delta \right\} \tag{1}$$

$$V_\delta = \Sigma \left\{ \frac{1}{2} \times (\delta_i + \delta_{i-1}) \times \Delta S \right\} \tag{2}$$

Where, V_s: Amount of soil settlement, V_δ: Amount of soil lateral flow, S_i: Amount of settlement in i node, $\delta_{i:}$ Amount of lateral displacement in i node, ΔS: Node distance in vertical direction, Δδ: Node distance in horizontal direction

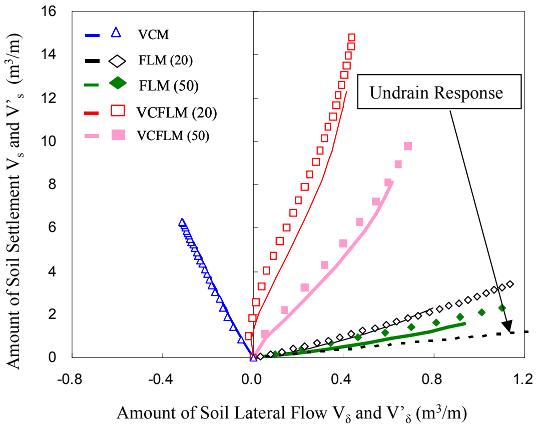

Figure 6. Relationship between amount of soil settlement and lateral flow due to fill speed

Amount of soil settlement (V_S) and amount of lateral flow (V_δ) values calculated above by equation (1) and (2) and plotted figure 6 according to FCM, VCM and FLVCM due to fill speed 20 cm/day and 50 cm/day respectively. In this figure, the dotted line is un-drained response that shows the deformation stage of the ground where V_S=V_δ is satisfied. Un-drain response in closer behavior is shown in the FCM cases and also case 50cm/day is more remarkable compare to another cases and is understood that the cases with fill construction shows deforming behavior like the neighborhood shearing deformation as a un-drain response. Observation in here, the period of fill rest that means after filling both cases are shown strong rebound tendency with increases amount of settlement because is not occurred consolidation, usually after fill soft ground tendency becomes to initial stage without consolidation pressure. But as for the result of VCM is understand of the appearance that V_δ increased the minus axis with increasing the settlement and it is understand that relation of Vs> -V_δ is occurred superior settlement behavior with lateral shrinkage of the ground deformation. However, FLVCM cases tendency of V_S>V_δ relation is stronger than FCM cases and also it is understand from figure settlement behavior more superior in deformation mode. Moreover, it is estimated that the ground tendency has been shrunk rapidly according to the period of fill rest and fill is executed with 50cm/day, respectively.

However, these types of various deformations have some ground where the measurement becomes difficult according to the site. In that situation, usually, the amount of settlement (S) is measured on the site of the fill center, amount of horizontal displacement (δ) of the ground surface in the out of improvement area, amount of soil settlement (V_S') is rectangle and amount of soil lateral flow (V_δ') is triangle calculation method applied according to S, δ amount of soil deformation. They were tried to calculation the amount of soil deformation by following equation

Amount of soil settlement (V_S') = S×B (3)

Amount of soil lateral flow (V_δ') = δ×H/2 (4)

Where, V_S': Amount of soil settlement, V_δ': Amount of soil lateral flow, S: settlement in the center, δ: Lateral displacement on the ground surface, B: Width of improvement area, H: Thickness of improvement area

Amount of soil settlement (V_S') and amount of soil lateral flow (Vδ') according to the equation (3) and (4) with shown together V_S versus V_δ relation (during the fill construction) respectively. It is seen that correspondence between V_S versus V_δ (during the fill construction) and V_S' versus V_δ' (calculated according to site) relation is similar tendency (fig.6) of ground deformation depends on settlement in center (S) and lateral displacement on the ground surface (δ). Therefore, it is thought that deformation behavior is possible to manage by settlement in center (S) and lateral displacement on the ground surface (δ) according to the FLVCM.

5.2 Analysis that attention to loading of vacuum pressure

In this section, discussed about the influence that the loading of vacuum pressure and the fill speed caused on the deforming behavior of the soft ground. Fill speed is

Table 4. Loading of vacuum pressure cases

Case	Vacuum Pressure (kPa)	Fill Speed (cm/day)	Fill Height (m)	Period of Vacuum Pressure (day)
V-20(20)	-20	20	5	25
V-60(20)	-60			25
V-90(20)	-90			25
V-20(50)	-20	50		10
V-40(50)	-40			10
V-60(50)	-50			10
V-80(50)	-80			10
V-90(50)	-90			10

V: Fill Loading with **V**acuum Consolidation Method

20cm/day, 50cm/day and fill height is 5m respectively. Range of vacuum pressures -20kPa to -90kPa is changed that loading of vacuum pressure has been setting up on the model. A part of an analytical case is shown in table 4. An analytical model and the input parameters are similar as well as the above-mentioned as for this analysis. In this analysis, the ground behavior is evaluated by relation of settlement (S) and lateral displacement (δ) that discus above. As a criterion, it was taken standard value ($\Delta\delta / \Delta t$ ≤15~20mm/day) of horizontal displacement speed of edge point of the fill slope by VCM technological material (addition 2004)9).

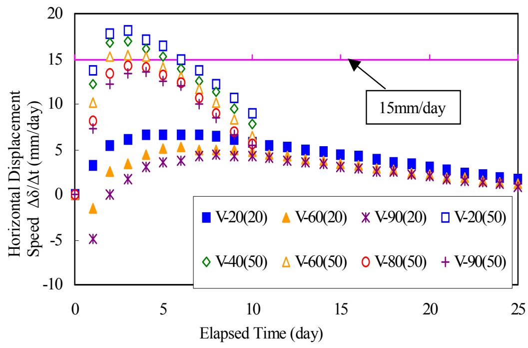

Figure 7. Plotted for horizontal displacement speed VS elapsed time by FLVCM of case studies

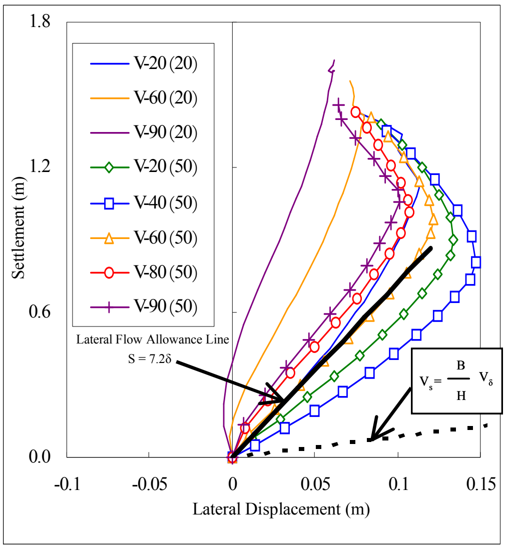

Fig. 8. Plotted for settlement VS lateral displacement

However, it was assumed that amount of lateral displacement of the ground surface in a point of 1.3m away from edge point of the fill slope or 10.1m away from center of the fill. Figure 7 shows relationship between horizontal displacement speed and elapsed time during fill construction to each case of FLVCM. The cases V-20(50) and V-40(50) that means fill speed 50mm/day and vacuum pressure less than –60kPa are exceeded 15mm/day of the maximum horizontal displacement speed, standard value has not been fulfilled in this figure. Moreover, the maximum horizontal displacement speed is shown 15.4mm/day as a case of V-60(50) that standard value has been satisfied or not in this analysis. Since, fill speed 50cm/day and vacuum pressure less than –60kPa cases are exceeded standard line but fill speed 20cm/day and all vacuum pressure cases are satisfied the standard line. So V-60(50) is a standard case that the approximation straight line is pulled as a satisfied the standard during the fill construction on the figure 8 plotted for settlement (S) versus lateral displacement (δ). In this figure, V-60(50) case is introduced on the approximation line as a lateral flow allowance line. It is understand that V-20(50) V-40(50) and V-60(50) cases are becoming on the deformation mode with especial superior lateral flow behavior according to S versus δ relation. Moreover, it can be determined that other cases has been shown stable behavior of S>δ strong tendency. Thus, it is proposed a stable construction management index concerning the lateral spreading by using S-δ relationship and the standard line in this research.

6. CONCLUSIONS

Numerical simulation by FEM when FCM, VCM, and FLVCM intended for the soft ground were executed. It is proposed construction management index to examine the utility of FLVCM by comparison with deformation ground behavior to obtain according to those analytical results. Moreover, numerical analysis to which attention was carried out to loading of vacuum pressure in also construction condition of FLVCM, deforming ground behavior was evaluated based on the proposed construction management index, and considered to influence that loading of vacuum pressure exerted on ground deformation behavior. It is described to have clarified points in this research as follows.

(1) Average vacuum pressure -69kPa (hydraulic head had been given –3.5m to the drainage boundary) in the vacuum pump was expressed by the analyses, to great result of accuracy was able to be obtained to

comparing the amount of settlement than previous research.

(2) Numerical simulation of FLVCM was carried out of fill consideration and more smaller element division made by analytical model. As a result, it was clarified that distribution in the ground of pore water pressure in vertical and horizontal direction by loading of vacuum pressure was expressible more in detail. Moreover, deformation ground behavior of general fill construction and VCM was compared during the fill construction, on that time clarified as an effect of using FLVCM as follows (a) Effect of controlling the ground deformation of circular slide as a center on fill edge point and great lateral shrinkage behavior. (b) Effect of rebound decrease that occurs after releasing vacuum consolidation pressure according to without fill construction. (c) Return to the initial stage of hydraulic pressure at fill rest period and controlling excess pore water pressure due to only on the general fill construction.

(3) About the 3 kinds of numerical simulation result that relation is taken out of the amount of soil settlement and lateral flow of the improvement area, un-drain response became a standard, and could be decided to deformation mode during the fill construction of each construction method. Moreover, settlement of fill center versus maximum horizontal displacement on the out side of improvement area and relation between amount of soil settlement versus lateral flow are similar deformation mode and also similar to calculated indirectly deformation mode relation respectively.

(4) Numerical simulation was carried out by attention of the vacuum pressure on the condition of FLVCM that fill speed 50cm/day and vacuum pressure less than –60kPa cases are suggested becoming unstable from behavior of settlement and excessive pore water pressure. Moreover, it was clarified that the lateral spreading behavior especially exceeded the standard line than fill speed 50cm/day and vacuum pressure less than –60kPa, since the standard line of lateral spreading allowance line was originally introduced from a FLVCM standard specifications based on the reference value at the horizontal displacement speed under construction and the ground behavior was evaluated.

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