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Dissipation Behavior of Excess Pore Water Pressure in Sand Mat using Dredged Soil

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ABSTRACT: The design of sand mat should be reviewed by behavior of excess pore pressure which is obtained by combining characteristics of soft ground with the permeability of sand mat. In this paper, in order to investigate the distribution of hydraulic gradient of sand mat, a banking model test was performed using dredged sand as materials of sand mat, and these results were compared by the numerical analysis results utilizing Terzaghi's consolidation equation. As the results, it shows that the pore pressure was influenced by the settlement increasing in the center area of sand mat as the height of embankment increases, and uprising speed of excess pore pressure due to residing water pressure is delayed comparing with the results of numerical analysis. Sand mats should be laid to reduce the increased hydraulic gradient at the central part of the embankment.

Keywords: Dredged Soil, Sand Mat, Model Test, Excess Pore Water Pressure, Pressure Head

1. INTRODUCTION

Sand mat is used as a horizontal drainage method during embankment to facilitate the initial consolidated settlement due to the weakness of the surface layer of dredged and reclaimed sites, and this construction method is applied in general areas of soft soil ground. In particular, due to the insufficient amount of sand in dredged and reclaimed areas and areas of soft soil ground, there is a desperate need to procure alternative materials, which has increased the need for research on using quality dredged soil as a sand mat.

Thus, in order to determine whether dredged soil is a suitable material to be used as a sand mat, a large sample was collected for physical properties analysis and permeability testing. Based on the results, the representative dredged soil (of the samples with permeability coefficients that fit the criteria for sand mat, the sample with the worst particle size as it contains the most amount of fine powder) was selected and a model test was conducted to determine its applicability as a sand mat in advance. The distribution of pore water pressure and the drainage of the sand mat, which is necessary in the improvement of soft soil ground, were identified and the amount of consolidated settlement according to the embankment load was measured in order to perform a finite-element analysis and predict its behavior. After the consolidation was completed by the final load, a discharge test was performed and the effect of the permeability was observed. The aim of this study is to apply the theoretical review to the design by proposing a testing technique that can be utilized on sand mat, and improving the technology of utilizing alternative materials for sand mat based on the results.

2. THEORETICAL WATER PRESSURE DISTRIBUTION FOR A SAND MAT

The pore water pressure of sand mat laid on the soft clay ground generally increases in proportion to the amount of settlement in the clay layer according to Terzaghi's theory of one-dimensional consolidation (Terzaghi, 1943, Terzaghi, et al., 1967). The increased excess pore water pressure is quickly drained out from the embankment body due to the permeability of the sand mat. However, as shown in Fig. 1, if the permeability of the sand mat is low or there is large settlement of the soft clay ground, drainage is delayed in the central part of the embankment, which increases the pressure head. In Fig. 1, it is assumed that the amount of consolidated settlement in the saturated clay layer generated by the embankment load undergoes a one-dimensional change and the pore water from consolidation is completely drained out from the embankment body in a horizontal direction through the saturated sand mat. Thus, for saturated clay ground, the consolidated settlement of the clay layer can be represented as a function of the average degree of consolidation (U) and time (t) according to Terzaghi's consolidation equation. The pressure head (H) occurring at the horizontal distance (x) of the sand mat can be presented as Eq (1) according to Terzaghi's one-dimensional consolidation equation.

$$H = \frac{\gamma_w}{2k \cdot T} \cdot \frac{dU(t)}{dt} \cdot \left(S_{0f} \cdot x - \frac{S_{0f} - S_{Df}}{2L} \cdot x^2 \right) dx \tag{1}$$

where dU(t)/dt is the settlement rate of the clay layer, S_{0f} is the final amount of settlement in the center of the embankment, S_{Df} is the final amount of settlement in the

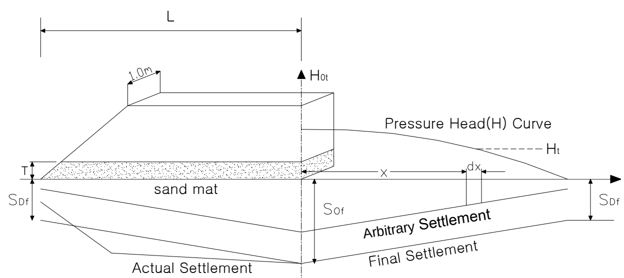

Fig.1 Distribution of pressure head of sand mat

sides of the embankment, T is the thickness of the sand mat, k is the permeability coefficient of the sand mat, 2L is the full width of the sad mat, and γ_w is the unit weight of water. Because Eq (1) assumes a one-dimensional, horizontal flow of the pore water from the sand mat, the pressure head is zero (H=0) at the sand mat boundary (x=L). Thus, when the maximum pressure head at the center of the embankment is set as H_{0t} and the average pressure head in the transverse distribution is indicated as H_t, the pressure heads can be presented as follow in Eq (2) and Eq (3).

$$H_{0t} = \frac{\gamma_w}{2k \cdot H}\left(\frac{S_{0f}}{3} + \frac{S_{Df}}{6}\right)L^2 \cdot \frac{dU(t)}{dt} \tag{2}$$

$$H_t = \frac{\int_0^L h \cdot dx}{L} = \frac{\gamma_w \cdot L^2}{2k \cdot T}\left(\frac{5S_{0f}}{24} + \frac{S_{Df}}{8}\right)\frac{dU(t)}{dt} \tag{3}$$

In Eq (2) and Eq (3), the pressure heads of the sand mat vary depending on the settlement rate, final amount of settlement, sand mat thickness, permeability coefficient, and the width of the embankment. Here, the settlement rate can be obtained from the approximation formula of the relationship between the degree of consolidation (U) and time factor (T_v) in Terzaghi's one-dimensional consolidation equation and the measured settlement as follow in Eq (4) and Eq (5).

$$S_f = \frac{C_c}{1+e_0} \times H \times \log\frac{P_0 + \Delta p}{P_0} \tag{4}$$

$$U(\%) = \sqrt{\frac{4}{\pi}T_v} = \sqrt{\frac{4}{\pi} \times \frac{C_v \cdot t}{H^2}} = \frac{S_t}{S_f} \times 100 \tag{5}$$

In Eq (4) and (5), S_f is the final amount of settlement, whereas S_t is the amount of settlement at an arbitrary time and the other coefficients have the same symbols as those in Terzaghi's one-dimensional consolidation equation.

3. MODEL TEST ON BEHAVIOR OF PORE WATER PRESSURE IN SAND MAT

3.1 Experimental Apparatus and Method

For the model test, head devices were designed to be placed on both sides of the soil tank (dimensions: 300cm × 70cm × 70cm) to maintain the groundwater inside the sand mat at a constant level, and 4 pore water pressure cells, 3 settlement plates and 2 earth pressure cells were installed to measure the amount of settlement of the clay layer and sand mat and the pore water pressure during embankment loading. The soft clay in the bottom of the sand mat was sufficiently stirred with distilled water using an electric agitator in a simple soil tank, and the slurry was inserted up to a height of 30cm. Then, saturated water was supplied for approximately a week by the head devices until a steady state was reached. Later, a sheet was laid, upon which dredged soil was spread to a height of 20cm in place of the sand mat. The drainage valves on the left and right sides (Fig. 2) were closed and saturated water was supplied for a day. Then, spreading and loading were performed up to the third level using weathered soil.

3.2 Physical and Mechanical Properties of Sand Mat and Clay

The physical properties and particle distribution of dredged soil used in this experiment are shown in Table 1 and Fig. 3. Fig. 3 also contains information on the general particle distribution of sand mat applied in general soft soil ground designs. The dredged soil used in this experiment is slightly poor compared to quality sand as it is close to the lower limit of the fine materials used for sand mat, but it is deemed to have a good alternative to other materials for sand mat. In order to examine the consolidation characteristics of the lower clay used in this experiment, overconsolidated clay was turned in a slurry form using an agitator. Then, the consolidation sample was produced using a consolidation device. The standard consolidation characteristics of the test sample and the input moisture content (w_n), etc., of the slurry form inserted into the model soil tank are shown in Table 2.

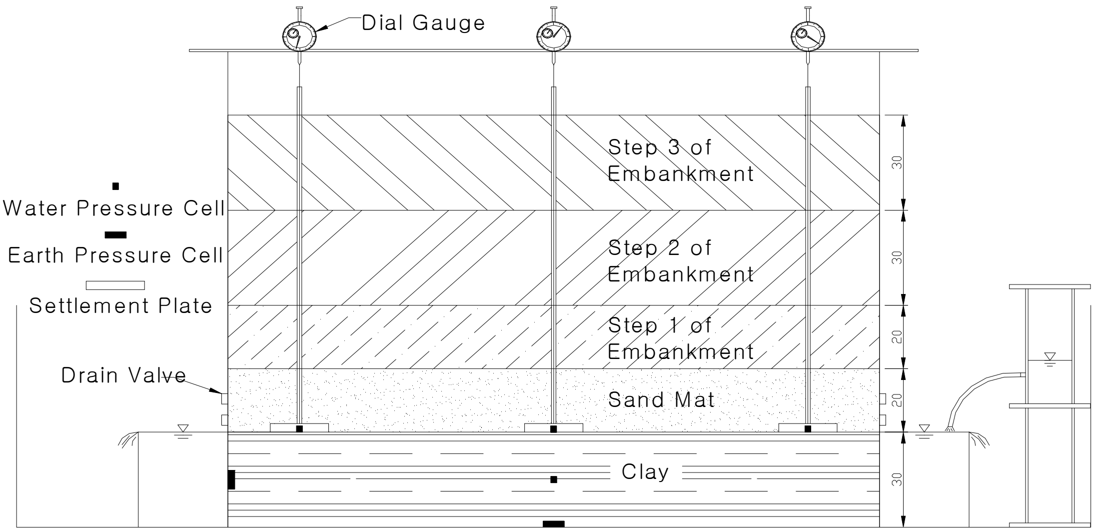

Fig.2 Model test for hydraulic gradient of sand mat (unit: cm)

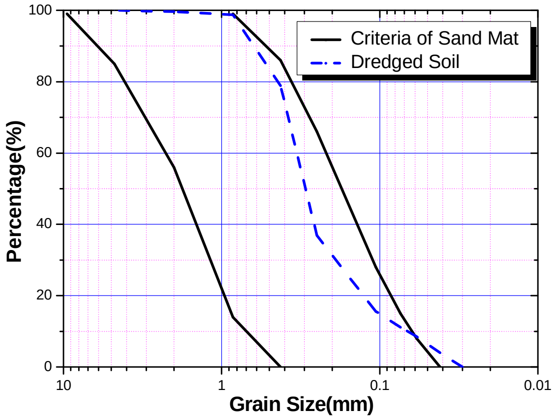

Fig.3 Pressure head distribution of a sand mat

Table 1 Physical properties of sand mat used in experiment

Water Content (%)	17.6
Plasticity Index (I_p)	NP
Specific Gravity (G_s)	2.60
Passing 75 μm sieve (%)	9.5–13.3
Coefficient of Permeability (cm/sec)	1.34×10^{-3}
USCS	SM

Table 2 Physical and mechanical properties of remolded clay

Water Content (w_n, %)		54.5
Unit Weight (γ_t, kN/m^3)		16.6
Specific Gravity (G_s)		2.60
Consolidation	e_0	1.26
	C_c	0.380
	C_s	0.159
	C_v (cm^2/s)	1.56×10^{-4}
	P_c (kPa)	10
USCS		CL

Table.3 Amount of settlement and ground stress measured during embankment

		S_{Df} (cm)	S_{0f} (cm)	Δp (kPa)
Sand Mat		0.89	1.33	3.4
Embankment	Step 1	1.35	1.87	3.6
	Step 2	1.76	2.32	5.1
	Step 3	2.04	2.62	5.1

3.3 Settlement Characteristics According to Embankment

For the embankment, the degree of consolidation was confirmed to be over 90% using the hyperbolic method (Tan, et al., 1991) and loading was performed in 3 steps up to a height of 100cm over the course of 11 days. The degree of consolidation according to the settlement of the clay ground was assessed using the ratio of the amount of settlement actually measured through the model test and the final amount of settlement calculated using the specifications of the consolidation test. The final amount of settlement was calculated based on the initial void ratio according to the input moisture content and the ground stress (Δp) measured using the earth pressure cell at the bottom of the clay layer. The measured values (Δp) of the earth pressure cell at the center, the amount of settlement (S_{0f} and S_{Df}) measured using the dial gauge at the center and the left and right fore-ends in the model test device (Fig. 2) during the embankment are shown in Table 3.

4 NUMERICAL ANALYSIS OF PORE WATER PRESSURE OF SAND MAT

4.1 Pore Water Pressure According to Permeability Coefficient and Thickness of Sand Mat

The settlement rate (dU(t)/dt) for the initial consolidation degree (U) of 3%, obtained when the clay layer thickness of 30cm and consolidation coefficient in Table 2, are substituted into Eq (5) and the amount of settlement at the center of the embankment (S_{0f}) and the amount of settlement in the outer part of the embankment (S_{Df}) measured at step 3 of embankment, and the spread thickness (T) of 20cm, were substituted into Eq (2). When the permeability, k, changed up to $10^{-4}\sim10^{-2}$ (cm/sec), the pressure head, H_t, was calculated according to the horizontal distance of the sand mat, and the results are shown in Fig. 4. As shown in the figure, the lower the permeability coefficient of the sand mat, the higher the hydraulic gradient at the center of the embankment, which in turn increases the pressure head. In particular, there is a significant increase in the pressure head when the permeability coefficient of the sand mat is below 10^{-4} (cm/sec) as it causes a delay in the draining of pore water. Also, the settlement rate calculated when the degree of consolidation was 3% using Eq (2), the amount of settlement at the center of the embankment (S_{0f}) and the amount of settlement in the outer part of the embankment (S_{Df}) measured at step 3 as shown in Table 3 were substituted into the equation, with the permeability coefficient, k, maintained at a constant of 10^{-3} (cm/sec). Then the thickness of the sand mat (T) was varied in the range of 5 to 30cm to analyze the resulting value of the pressure head, the results of which are shown in Fig. 5. The figure shows that with an increase in the thickness of the sand mat, the pressure head decreased, and the change in the pressure head was small in the outer part of embankment as it is less affected by the hydraulic gradient.

4.2 Pore Water Pressure of Sand Mat Based on Coefficient of Consolidation in Clay Layer

In order to analyze the pressure head of the sand mat according to the settlement rate of clay in the bottom, the coefficient of consolidation (C_v) was selected as a factor affecting the settlement rate in the clay layer. when the consolidation coefficient (C_v) of the clay layer is changed up to the range of $10^{-5}\sim10^{-3}$(cm^2/sec) with the initial degree of consolidation (U) at 3%, the consolidation time (t) for the arbitrary consolidation coefficient can be calculated using Eq (5) and thus, the settlement rate (dU(t)/dt) with respect to the degree of consolidation can be obtained. Thus, the amount of settlement at the center of the embankment (S_{0f}) and the amount of settlement in the outer part of the embankment (S_{Df}) measured at step 3 as shown in Table 3 and the permeability coefficient, k, a constant of

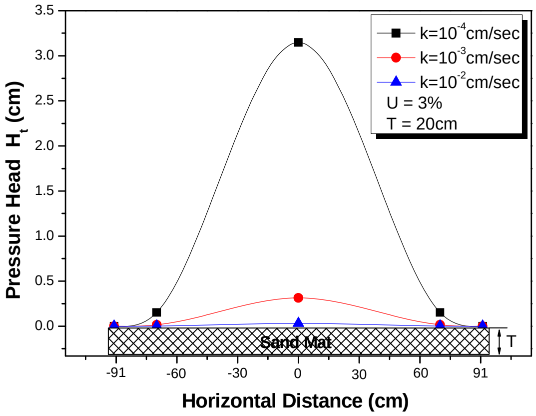

Fig.4 Pressure head according to changes in permeability coefficient

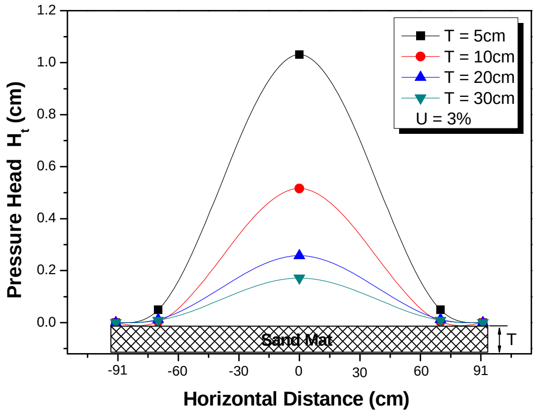

Fig.5 Pressure head according to changes in thickness of sand mat

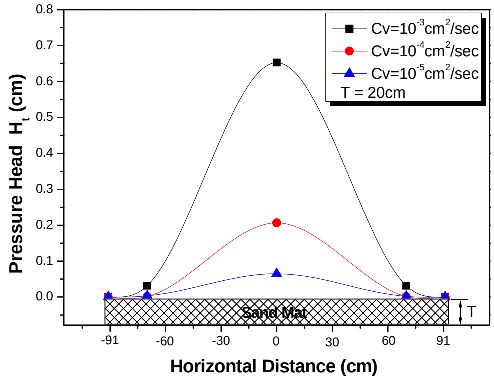

Fig.6 Pressure head according to changes in consolidation coefficient

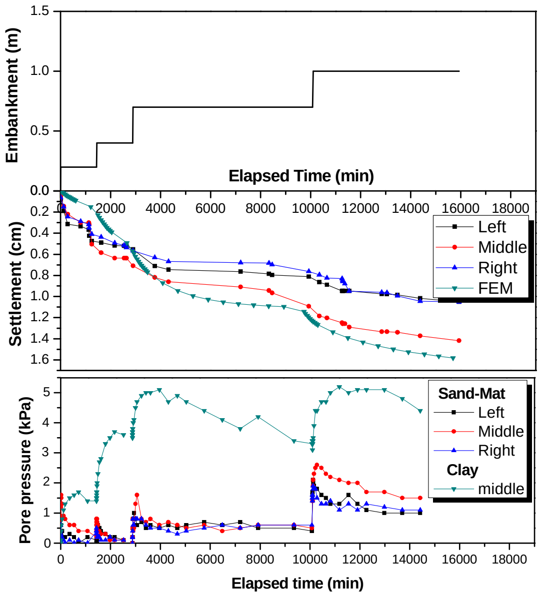

Fig.7 Pore water pressure of sand mat and settlement and pore water pressure of clay ground

10^{-3} (cm/sec), were substituted into Eq (2) to obtain the pore water pressure in the sand mat. The results are shown in Fig 6, which shows a positive correlation between the consolidation coefficient of the clay layer and the pressure head at the center of the embankment. This is due to the increase in the amount of consolidation drainage resulting from the increased settlement rate of the clay layer caused by increased stress at the center of the embankment.

5 ANALYSIS AND DISCUSSION OF RESULTS

5.1 Excess Pore Water Pressure of Sand Mat According to Height of Embankment

The top of Fig 7 shows the results of the FEM analysis conducted based on the modified cam-clay model (Snadhu, et al., 1969, Mayhe, 1980, Gens, 1988) of the settlement, measured in the settlement gauges installed in the left, central and right parts of the sand mat layer, according to the elapsed time during embankment. The bottom of the figure shows the measurements of the pore water pressure cells installed inside the sand mat layer and at the center of the clay layer.

As the height of the embankment increased, there was a higher amount of settlement in the central part of the clay layer compared to the left side. Because of the soft surface and the low shear strength, there was a immediate settlement during the laying of the sand mat and the primary embankment, and the actual measurement of the settlement was higher than the settlement calculated based on FEM analysis. Afterward, the measured settlement and the result of the FEM analysis tended to be similar, but the actual settlement was slightly smaller due to the buoyancy effect caused by inhibited drainage during the experiment. Also, a comparison of the pore water pressure in the clay layer and sand mat layer during embankment showed a significant increase of pore water pressure in the clay layer, whereas such increase was prominent at the center and low in the left and right sides of the sand mat layer. This is due to the increased hydraulic gradient caused by an increase in the residual pore water pressure resulting from the concentrated stress in the central part of the clay layer.

Fig. 8 to 11 show the results of the pore water pressure measured using the pore water pressure cells installed in the sand mat and the clay layer according to the embankment during the model test. Fig. 8 shows a rapid increase of pore water pressure caused by soil disturbance and the groundwater level remaining at the top of the saturated soft clay layer. The pore water pressure increased up to 1.6kPa at the center of the sand mat, and gradually decreased over time until it reached 0.6~0.4kPa after 400 min. Fig. 9 shows the result of the pore water pressure measured during the primary embankment, which slightly increased at the center to a maximum of 0.8kPa and greatly increased in the left

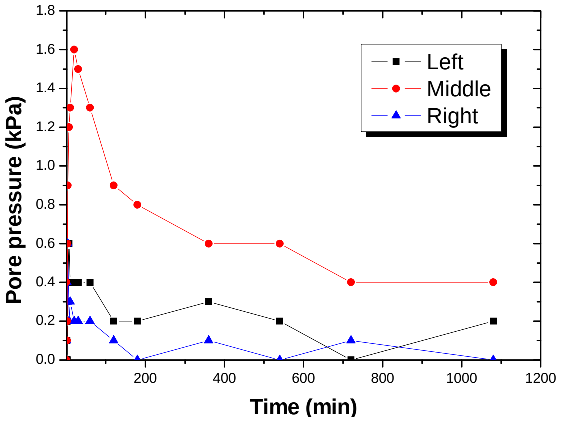

Fig.8 Changes in pore water pressure during laying of sand mat

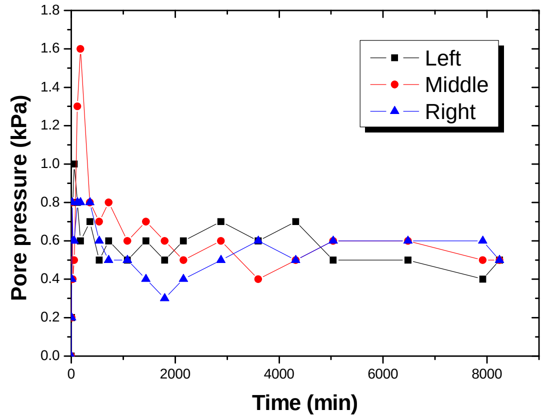

Fig.10 Changes in pore water pressure during step 2 of embankment

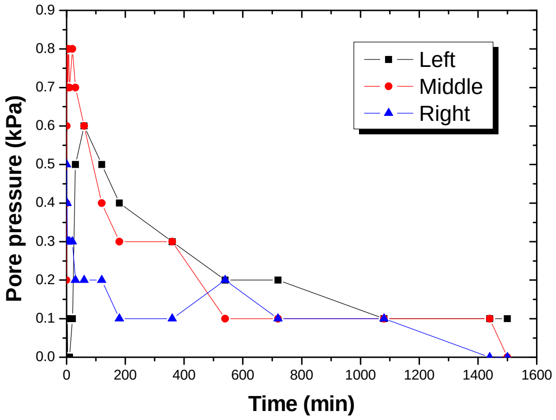

Fig.9 Changes in pore water pressure during step 1 of embankment

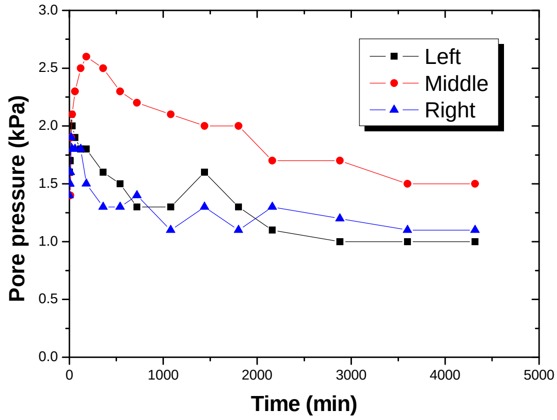

Fig.11 Changes in pore water pressure during step 3 of embankment

and right sides to a maximum of 0.6kPa in comparison with the loading of the sand mat. Fig. 10 shows the pore water pressure measured during the step 2 of embankment. The pore water pressure at the center increased up to 1.6kPa at initial loading before decreasing to approximately 0.5kPa over time. The bottom clay foundation subsided uniformly until the step 2 of embankment, which showed that the sand mat has maintained the horizontal function. The changes in the pore water pressure of the sand mat at the time of final embankment shown in Fig. 11 revealed that there was a significant increase of pore water pressure in the central part of up to 2.6kPa and in the left and right sides of up to 2kPa during initial loading compared to the step 2 of loading. Over time, the pore water pressure in the central part of the sand mat was observed to be higher than the left and right sides, with a constant slope. There was an increase of settlement at the center of the embankment and the sand mat formed a concave shape, which caused the pore water to form a pool as it could not be drained out.

5.2 Pressure Head of Sand Mat According to Degree of Consolidation in Clay Layer

In order to compare and identify the tendency of the water head of the sand mat according to the degree of consolidation in the clay layer during the embankment based on theory and experiment, the pressure head measured using the pore water pressure cells installed in the sand mat and the pressure head predicted using Eq (2) are indicated in Fig 12 and 13. The thickness and consolidation coefficient of the clay layer in the experiment were substituted into Eq (5) to obtain the settlement rate (dU(t)/dt) with respect to the predetermined degree of consolidation, which was then substituted into Eq (2) to calculate the pressure head. Then, the degree of consolidation of the clay ground was obtained using the ratio of the amount of settlement (S_t) measured through the model test and the final amount of settlement (S_f) calculated using Eq (4). The pore water pressures of the laboratory clay ground corresponding to the predetermined degree of consolidation are indicated in Fig 12 and 13. An analysis of the step 2 and step 3 of embankment, which caused a significant increase in the pore water pressure, showed that the pore water pressure of the sand mat measured during the step 2 of embankment in the model test was generally higher due to the increase in the degree of consolidation compared to the result of the numerical analysis. The measured pore water pressure was at its maximum at the center when the degree of consolidation was 26% and at the left and right sides when the degree of consolidation was 14%. On the other hand, the result of the numerical analysis revealed that the maximum pore water pressure was reached when the degree of consolidation was 5%. Fig. 13 shows that the pore water pressure was measured to be at its maximum at the center during the step 3 of embankment when the degree of consolidation was 14% and at the left and right sides when the degree of consolidation was 5% and 14%. On the other hand, the result of the numerical

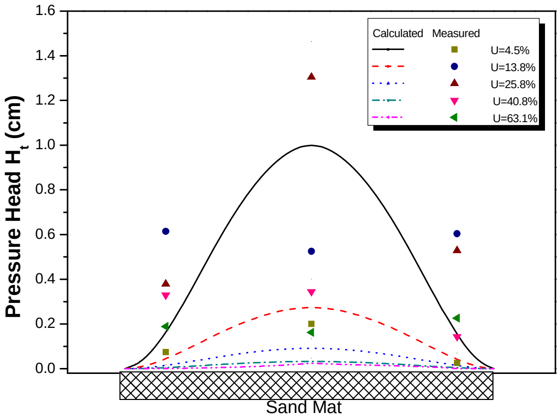

Fig.12 Comparison of measured results and numerical analysis results of pore water pressure according to degree of consolidation during step 2 of embankment

analysis revealed that the maximum pore water pressure was reached when the degree of consolidation was 5%, just as with the step 2 of embankment. In the case of step 3 of embankment where the height of the embankment is greater, the pore water pressures measured in the left and right sides were higher compared to the values measured during the step 2 of embankment, and with an increase in the degree of consolidation, the measured values for the left and right sides of the sand mat were greater than the results of the numerical analysis. As the embankment grew taller, there was an increase of settlement in the central part of the sand mat, causing a deformation, which inhibited drainage.

6 CONCLUSION

In this study, the pressure head distribution of a sand mat laid on a clay layer was analyzed based on Terzaghi's one - dimensional consolidation, which takes into consideration the settlement characteristics of the bottom clay layer. Also, the effect of the settlement characteristics of the soft clay layer on the pore water pressure distribution of the upper sand mat layer was reviewed based on the model loading test. The findings of this study can be summarized as follows:

(1) Terzaghi's one-dimensional consolidation equation, which takes into account the rate of consolidated settlement in the clay layer and the settlement level, is highly influenced by the permeability coefficient and thickness of the sand mat and the consolidation coefficient of the clay layer.

(2) Because the settlement level of the embankment center increases pressure head, it reduces the horizontal drainage of sand mat.

(3) The reason for the delay in the drainage of the pressure head measured during the test compared to the result of the numerical analysis is the increased hydraulic gradient occurring because the increased settlement in the central part is transferred to the left and right sides.

(4) The amount of settlement in the central, left and right sides should be predicted prior to the laying of the sand mat in order to reduce the hydraulic gradient and the horizontal water head resistance in the sand mat.

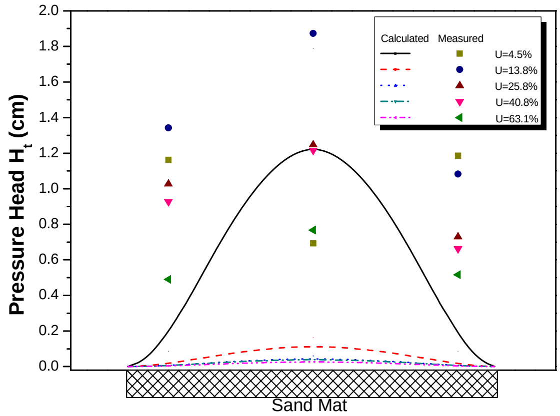

Fig.13 Comparison of measured results and numerical analysis of pore water pressure according to degree of consolidation during step 2 of embankment

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