A method of monitoring water flow in prefabricated board drain to estimate consolidation progress

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ABSTRACT

The authors have proposed a simple design method of the VD using PBD materials for horizontal drainage. This design method is the comparison of the required flow volume \( q_A \) calculated from a Barron type equation and the drainable amount \( q_V \) computed by solving simultaneous equation of the flow network. It was obvious that the measurement of flow quantity of the actual drain networks was important to prove the validity of this design method. Therefore, the flow quantity in the PBD network was measured in the PBD construction site of Osaka Bay area by applying temperature change of the flow water. As the results of this research, the followings were obtained: 1) It was proved to be applicable to measure flow quantity in PBD material from the two sets of thermocouples inserted. 2) As a result of observation, the measured value of the flow quantity in PBD was close to the predicted one especially for a vertical drain part. 3) It seems that the network of the vertical and horizontal PBD drain works effectively and consolidation is promoted smoothly. This means the use of PBD material as a substitute of sand mat might be practical for vertical drain method.

Keywords: plastic board drain, horizontal drainage, in-situ flow measurement, soft ground

1 BACKGROUND

Among techniques to improve a soft ground, the vertical drain method (hereinafter called "VD method") is a technique to promote consolidation settlement of a soft ground by installing a vertical drainage material in the ground with surcharge and vacuum pressure. For the plastic board drain ("PBD") method, which is one of those techniques, is a technique that uses a plate-like prefabricated drainage material called PBD material for vertical drainage material and permeable sand mat for horizontal drainage generally. However, since it has become difficult recently to obtain high quality sandy soil suitable for sand mat, the number of cases that PBD materials are also applied for horizontal drainage has been increasing. However, there have not been established design methods for VD methods utilizing PBD materials for horizontal drainage and therefore it has been required to develop a simple and practical design method. Conventional, although the theory of Yoshikuni\(^1\), which considers consolidation delay caused by the mat resistance, has been known for designing the VD method, Fukuda et al.\(^2\) considered that the theory overestimates consolidation delay for actual on-site construction, and therefore they have proposed a double drainage layers model, developing a concept called "peristyle tank models" for an analytic technique of consolidation delay using compound horizontal drainage layers with a horizontal drainage layer of PBD on the lower part and a horizontal drainage layer of filling on the upper part. For these models, in the proposed method the upper part filling layer, which can hardly be quantified, is ignored and it is assumed that all drainage passes the PBD materials, which are horizontal drainage materials.

2 STUDY PURPOSE

The authors have proposed a simple design method to examine consolidation delay of each drain by comparing water conduction performance for one drain evaluated by Kamon et al.\(^3\) (hereinafter called "required flow volume \( q_{i,r} \)") based on the conventional Barron's\(^4\) formula and drainable amount in each drain calculated by the design method (hereinafter called "drainable amount \( q_{i,d} \)). This time, based on the design method\(^5\) that have been proposed so far, we have proposed a method to examine consolidation delay of each drain according to consolidation time, and examined its adequacy by the flow-speed measurement in drain materials in the actual PBD construction site.
3 PROPOSED DESIGN METHOD

As shown in Fig.1, drainage from soft strata by consolidation repeats merging to the horizontal drain before it is drained outside. This is expressed with a continuous equation shown in Eq.1. Substituting Eq.2 and 3 into Eq.1, Eq.4 is obtained.

\[ q_{2,1} = q_{1,3} \]
\[ q_{1,3} + q_{4,3} = q_{3,5} \]
\[ q_{2n-3,2n-4} + q_{2n-1,2n-1} = q_{2n-1,2n+1} \]
\[ q_f = k_f \times h_f \times b_{V} \times t_V \]
\[ q_H = k_H \times h_H \times b_{H} \times t_H \]

\[
\begin{align*}
(x + y)h_i - yh_j &= xh_i \\
-yh_{i-1} + (x + 2y)h_{i-2} - yh_{i-1} &= xh_{i-1} \\
&\vdots \\
-yh_{i-1} + (x + 2y)h_{i-2} - yh_{i-2} &= xh_{i-2} \\
&\vdots \\
-yh_{i-1} + (x + 2y)h_{i+2} - yh_{i+1} &= xh_{i+1} \\
&\vdots \\
-yh_{i-1} + (x + 2y)h_{i-1} - yh_{i-1} &= xh_{i-1}
\end{align*}
\]

Here, \( h_2, h_4, \ldots, h_{2n} \): water head of the center part of the vertical drain, \( h_1, h_3, \ldots, h_{2n-1} \): water head at the joint of the vertical and horizontal drains, \( h_{2n+1} \): water head of the horizontal drain's drainage end (= 0 kN/m²), \( q_f \): flow rate of the flow from \( h_1 \) to \( h_4 \), \( x = k_1, b_1, t_1, l_2, y = k_2, b_2, t_2, l_1 \). The design method proposed in this paper is a simple design method with which water conduction performance of each drain is evaluated from the drainable water amount \( q_f \) calculated and the flow volume required for one drain \( q_A \) to examine consolidation delay of each drain. Eq.5 proposed by Kamon et al. \(^3\) is used for the required flow volume \( q_A \).

\[ q_A = U \times F_s \times S \times \frac{\pi \times c_s}{4} \times T_h \]

Here, \( q_A \): flow volume required for the drain (cm³/sec), \( U \): Degree of consolidation (%), \( F_s \): Safety factor, \( S \): Settlement (cm), \( T_h \): Horizontal time factor, \( c_s \): Horizontal coefficient of consolidation (cm²/day).

Based on the Barron's theory, the flow volume \( q_A \) required for one vertical drain \( q_A \) in the case that consolidation delay is not present is obtained from Eq. 5. On the other hand, drainable amount \( q_{\text{old}} \) is calculated from the continuous equation of Eq.3 on the condition of excess pore water pressure of the vertical drain's central part, which is back-calculated from the required flow volume \( q_{\text{old}} \) of one step before, and the water head of the horizontal drain's drainage end = 0 kN/m². Calculation for the next step is performed by the magnitude relation of the \( q_{\text{old}} \) and \( q_{\text{old}} \). In other words, in the case that the drainable amount \( q_{\text{old}} \) and required flow volume \( q_{\text{old}} \) meets the Eq. 6, drainage by the drain is performed smoothly and therefore consolidation delay does not occur.

Next, in the case that the relation of the drainable amount \( q_{\text{old}} \) and required flow volume \( q_{\text{old}} \) do not meet the Eq.6, drainable amount \( q_{\text{old}} \) in the consolidation degree \( U_{\text{old}} \) at the consolidation time \( t_{\text{old}} \) of the previous step is smaller than the required flow volume \( q_{\text{old}} \) and therefore drainage is piled up in drain and consolidation delay occurs.

4 ON-SITE FLOW RATE MEASUREMENT

In order to examine the adequacy of this design

| GL+2.5m | Filled Materials |
|---------|------------------|
|        |                  |
| GL+2.5m |                  |
| GL−2.00m |                  |
|        | Clay layer 1     |
|        | \( \varepsilon_{\phi} = 1.6 \quad C_e = 0.6 \quad c_v = 100 \text{ cm}^2/\text{day} \)|
|        | \( \rho = 20.55 \text{ kN/m}^2 \)|
| GL−2.00m | Clay layer 2     |
|        | \( \varepsilon_{\phi} = 1.7 \quad C_e = 0.8 \quad c_v = 60 \text{ cm}^2/\text{day} \)|
|        | \( \rho = 70.44 \text{ kN/m}^2 \)|
| GL−2.50m | Clay layer 3     |
|        | \( \varepsilon_{\phi} = 1.3 \quad C_e = 0.45 \quad c_v = 120 \text{ cm}^2/\text{day} \)|
|        | \( \rho = 108.99 \text{ kN/m}^2 \)|
method, the flow-speed measurement in PBD materials was performed in landfill banking work for surplus soil in the shield work of Hanshin Expressway Yamato River Line in Suminoe-ku, Osaka-shi.

This report presents results of the measurements conducted for 6 days in total from August 6, 2013 to January 29, 2014. Fig. 1 shows profile of the soft ground. Table 1 shows the calculation conditions. The site is to be developed with landfill material on its soft cohesive soil layers, and H = 6.25m of filling is to be given after a vertical and horizontal drains are placed. Measurements were performed on the horizontal drain for Survey point 1, and vertical and horizontal drains for Survey point 2, respectively (hereinafter called S1, S2).

Fig.3 shows details of S2. For S2-1, measurements were performed on two points in the eighth vertical drain from the underdrain trench and two points on the horizontal drain adjacent to a joint of the vertical drain. For S2-2, measurements were performed on the horizontal drain connected with the fourth vertical drain from the underdrain trench. For S2-1, we initially planned to set a flow-speed measurement unit on the ninth vertical drain from the underdrain trench, the sensor was actually installed 75cm away from the planed installation position to the opposite side of the underdrain as an eighth vertical drain.

The site flow-speed measurement was performed in accordance with the measurement principle6)7) shown in Fig.4. Assuming the time points when the water flow in the PBD material heated by a heater passes the thermocouples on the first and second rows and temperature rise begins as \( t_1 \) and \( t_2 \), respectively, time difference for the flow between the two points \( t = t_2 - t_1 \) is calculated. Further, the flow velocity \( v \) is calculated by dividing the setting distance between the two sets of thermocouples by the time difference \( t \).

5 RESULT AND DISCUSSION

5.1 PREDICTION BY THE DESIGN METHOD

A flow velocity in the drain materials was predicted by the proposed design method from the site calculation conditions shown in Table 1. Fig. 5 shows prediction of the site consolidation settlement. Since it is supposed that filling is loaded over four phases in the prediction, temporal change in settlement of each phase is calculated with settlement in each filling phase as 70cm. Moreover, the total settlement is calculated by overlapping them on the filling start time of each phase. Further, for each filling period, consolidation settlement to \( t = 800 \) day is predicted with \( H = 1.5m \) for 100 day, \( H = 3.0m \) for 200 day, \( H = 4.5m \) for 100 day and \( H = 6.25 m \) for the rest. Further, the final settlement is predicted as \( S = 280cm \).

Figs. 6 and 7 show layouts of the thermocouples of S2-1 and 2-2. Firstly, in prediction for the vertical drain, prediction methods are different between Heater 8 (upper) and Heater 17 (lower), which are shown in the layouts of the thermocouple in Fig.6. For Heater 8 (upper), drainage discharge for soft ground thickness of

Table 1 Calculation condition

| Item                        | Vertical D. | Horizontal D. |
|-----------------------------|-------------|---------------|
| Width b(cm)                 | 10.0        | 13.0          |
| Thickness t(cm)             | 0.3         | 0.5           |
| Cross sectional area A(cm²) | 2.43        | 6.00          |
| Length l(cm)                | 1980        | -             |
| Spacing d(cm)               | -           | 150.0         |
| Equivalent diameter d_e(cm) | 169.2       | -             |
| Equivalent diameter d_e(cm) | 5.0         | -             |
| Number of drains N          | 26          | 1             |
| Permeability of drain k(cm/sec) | 14.12  | 14.81         |
| Softground thickness H(cm)  | 1950        |               |
| Consolidation coefficient c_s(cm/sec) | 80    |               |
| Embankment height H(cm)     | 150 ~ 625   |               |
| Settlement S(cm)            | 70 ~ 280    |               |

Fig.3 Location of survey point S2-1, 2
19.5m in the vertical direction is subject for prediction while for Heater 17 (lower), only drainage discharge for 10.0m from the bottom end is taken into account since it is installed at the point 10.0m away from the bottom end of the soft ground thickness.

Next, in the proposed design method it is possible to predict flow velocity of the horizontal drain. It is calculated by multiplying the total drainage discharge for one vertical drain calculated from the Barron's equation by the number of the vertical drain, which is the measurement subject, based on the assumption that the total drainage discharge flowing through the horizontal drain is of the number of installed vertical drains from the center part of the embankment to the vertical drain. Further, the number of vertical drains installed from the center to the underdrain is \( n = 26 \), and the water flow at the measurement points increases as it flows towards the underdrain side from the center. Moreover, flow velocity in the horizontal drain is obtained by dividing the above by the drain's water flow cross section \( A' = 6.0 \text{cm}^2 \). Since consolidation delay did not occur under the conditions applied this...
time, values of Barron's equation corresponded well in the proposed design method. The result of the prediction by the above method has revealed that the flow velocity reached its peak after fill loading and flow velocity decreased after that.

### 5.2 MEASUREMENT RESULT

Fig.8 shows an example of temperature change at S2-1 vertical. The figure shows thermosensitive temperature change of thermocouples No.11-12 in layouts of vertical thermocouples at S2-1 vertical thermoelectricity in Fig.6. Since the result has revealed that the thermosensitive time difference of the two points is $t = 169 \text{ sec (} t_2 = 894 \text{ sec - } t_1 = 725 \text{ sec)}$ and the distance between the two points is 2.5cm, the flow velocity is $v = 2.5\text{cm}/169\text{sec} = 0.015 \text{ cm/sec}$. Likewise, we calculate flow velocity of S2-1-vertical in each measurement point and date and compare it with the values predicted by the proposed method. Fig.9 shows overall comparison between the predicted and measured values as for the flow-speed at the survey point S2-1 vertical. The result has revealed that the measured values are approximately 1.0-1.5 times greater in Fig.9 though tendency of the velocity variation is almost same, indicating the adequacy of the proposed design method.

Fig.10 shows temperature change at S2-1 horizontal. The figure shows temperature change of the thermocouples No.16-17 at S2-1 horizontal thermocouples' layouts in Fig.7. This figure does not clarify temperature change in the horizontal drain and therefore water flow is not confirmed. In contrast, Fig.10 shows that the temperature rise on the side that is away from the heater follows after that on the side that is close to it. Next, Fig.11 shows comparison between predicted values and measured values of flow velocity at S2-1-horizontal and S2-2-horizontal, respectively. The result shows that water flow is observed before and after the fill loading though it is not seen after that. In the case that filling rises up rapidly, excess pore water pressure by the fill loading is
drained to the horizontal drain and water flow occurs though flow velocity softens after that and temperature change is not recognized by the proposed method.

6 CONCLUSIONS

(1) The proposed model allows us to discuss on consolidation delay of each drain by comparing the required flow volume $q_A$ obtained by conventional Barron's equation and the method suggested by Kamon et al. and the drainable amount $q_V$ of each drain calculated by the proposed design method.

(2) It has been confirmed that it is possible to perform water flow measurement in drain materials by temperature measurement.

(3) The site observation result has revealed that measured values of water flow in a vertical drain were close to the predicted value obtained by the proposed design method. However, in a horizontal drain, water flow was confirmed immediately after fill loading though it was not after that. From the above result, it is thought that the role of the horizontal drainage material helps accelerating consolidation in the early stage of construction in particular.

(4) This study has revealed that it is sufficiently practical to use PBD materials as substitution of sand mat.

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