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Hayato Moro
Minoru Matsuo

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Case histories for settlement analysis in ground improved by vertical drain

Takaharu Shogaki and Hayato Moro
National Defense Academy
Hashirimizu, Yokusuka, Japan

Minoru Matsuo
Nagoya University
Furou, Chikusa, Nagoya, Japan

ABSTRACT

The effects of anisotropy and sample disturbance on the consolidation parameters were investigated through laboratory testing, and the degree of sample disturbance on the consolidation parameters in the periphery of the drain is evaluated. A new method for settlement analysis, taking into consideration both sample disturbance and the retardation of the consolidation in the ground improved by vertical drain, is proposed.

The effects of anisotropy and sample disturbance on the consolidation parameters in the ground improved by vertical drain are given as the function of the distance from the boundary of drain. In the undisturbed zone, the ratio of the coefficient of consolidation of the horizontal to the vertical is about 1.70, and in the completely remolded soil at the periphery of the drain, about 0.50. A new method for settlement analysis, taking into consideration both anisotropy and disturbance in the ground improved by vertical drain, is proposed. For the marine and the continental clay deposits in Japan, the accuracy of the prediction of the consolidation settlement by the proposed method under the degree of consolidation \( U=80\% \) are \( (7~\sim~20\%) \) for the marine clay deposits and \( (3~\sim~20\%) \) for the continental clay deposits.

KEYWORDS

Anisotropy, consolidation parameters, consolidation test, sample disturbance, settlement analysis, smeared zone, vertical drain

INTRODUCTION

Barron (1948) proposed the solution for the consolidation behavior of soils taking into account the disturbance in the periphery of the drain pile by drain installation. In Barron's solution, it is assumed that the area of the smeared zone is equivalent to the cross-sectional area of the drain, and derived the model which shared the periphery of the drain between the smeared zone and the undisturbed zone from the assumption that the soil in the smeared zone was an incompressible solid. Onoue(1988) proposed the solution taking into consideration the compressibility of the smeared soil. Onoue (1991) also carried out a model test simulating the drain installation, and showed that the model shared the periphery of the drain between an undisturbed zone and a smeared zone is reasonable in practice. However, he assumed in his solution that the smeared soil is homogeneous, and the coefficient of consolidation of the soil in the smeared zone is constant. In the case of improved ground by vertical drain, the effect of soil disturbance by drain installation becomes greater in proportion to the distance from the boundary of the drain, and an anisotropy of strength and consolidation parameters change in accordance with the distance from the boundary of drain. However, the change of the anisotropy of strength and consolidation parameters by soil disturbance has never been expressed as the function of the distance from the boundary of drain, and there is no solution of consolidation of soil by vertical drain, which takes change into consideration.

In this paper, the effects of anisotropy and sample disturbance on consolidation parameters are investigated through laboratory testing, and a new method for settlement analysis taking into consideration both the anisotropy and disturbance of soils is proposed to increase the reliability of design for settlement of ground improved by vertical drain. The applicability of the proposed method is also discussed. Finally, the proposed method is applied to the prediction of settlement for ground improved by vertical drain as the case history.

SOIL SAMPLES AND TEST PROCEDURE

The undisturbed soil samples used in this study were obtained from the Holocene marine clays located offshore at nine different clay deposits in Japan. In Matsuo et al. (1984),
the unconfined compressive strength \(q_u\) values obtained by a free piston sampler were about 40% smaller than those obtained by a stationary piston sampler. Therefore, field sampling was performed carefully by using a stationary piston sampler with an inner diameter of 75 mm to enhance the quality of the sampled specimens. In the case of Japanese soft clays, this sampler gives a quality similar to that sampled by the Laval type sampler (Tanaka et al., 1995). The index properties of these soils are shown in Table 1. These are saturated soils taken from the Hokkaido to Chugoku regions in Japan. The plasticity index \(I_p\) and \(q_u\) values are in the range of 30 to 98 and 14 to 177 kPa, respectively.

**Soil samples were disturbed in the laboratory using an extruder after setting up the disturbing equipment on the edge of the sampling tube (Shogaki et al., 1994). The specimens for the oedometer test were 60 mm in diameter and 20 mm in height. The specimens for the unconfined compression test were 15 mm in diameter and 35 mm in height (S specimen). These specimens, of which the major principal stress is at an angle of inclination (\(\beta\)) to the vertical, will demonstrate anisotropy of the strength and the consolidation, (Shogaki et al., 1994). The \(\beta\) values used in this study are 0° and 90°. The specimens of \(\beta = 0°\) and 90° are designated here as the vertical (v) and the horizontal (h) specimens, respectively. The effects of sample disturbance on the strength and the consolidation properties were determined for the S specimens. There is no difference in shear strength characteristics between the S specimen and the O specimen (80 mm in height and 35 mm in diameter), which were examined for soils of \(I_p\) and \(q_u\) of the range of 20 to 85 and 10 to 220 kPa, respectively (Shogaki, T. et al., 1991; Shogaki, T. et al., 1993).

There were four to seven specimens for each \(\beta\) for the unconfined compression test and one for the consolidation test. The \(q_u\) value is the mean value for \(q_u\) of the four to seven specimens. The oedometer tests reported here were conducted, using a load increment ratio of unity, and the duration of loading for each load increment was one day. The values of the coefficient of consolidation were determined according to Taylor's method (Taylor, 1948). The values of \(C_c\) and \(\sigma'_p\) were determined from the \(e\)-log \(p\) curves corresponding to 24-hour compression, where \(C_c\) is compression index, \(\sigma'_p\) pre-consolidation pressure, \(e\) void ratio, and \(\sigma'_{w}\) effective overburden pressure. Mikasa's method was used to identify preconsolidation pressure on the 24-hour e-log \(p\) curve. These methods have been employed in Japan as the Japanese industrial standard for the test method for one-dimensional consolidation properties of soils (JIS A 1217-1990).

**EFFECTS OF SAMPLE DISTURBANCE AND ANISOTROPY ON COEFFICIENT OF CONSOLIDATION**

Shogaki et al. (1995) performed the oedometer tests and the unconfined compression tests with the samples disturbed in different degrees. In the range of \(R(q_u) = 0.5 \sim 1.0\), the regression curve for \(e_v/e_h\) can be expressed as follows:

\[
c_v/c_h = 1.25 - 1.56 R(q_u) + 2.99 R(q_u)^2
\]

(1)

where, \(c_v\) and \(c_h\) are the coefficient of consolidation of v, h specimens, respectively. The \(R(q_u)\) is the ratio of the \(q_u\) value for disturbed sample to the undisturbed sample. Onoue (1991) carried out a model test simulating the drain installation in reconstructed Boston blue clay, and measured the change of void ratio in the periphery of the sand drain (SD) right after dissipation of pore water pressure caused by drain piling. The relationship between the ratio \(R(e)\) of the
void ratio of the disturbed soil \( (e) \) in the periphery of the drain to that of the undisturbed soil \( (e_0) \) and the ratio \( (r/r_w) \) of the distance \( (r) \) from the center of a drain to the radius of a drain \( (r_w) \) is shown in Fig. 1.

Figure 2 shows the relationship between the ratio \( (R(e)) \) of the disturbed sample void ratio \( (e) \) to the undisturbed sample void ratio \( (e_0) \) under the same \( \sigma_v' \) value of the undisturbed sample and the \( R(q_u) \). The \( R(e) \) values become smaller with increased sample disturbance. It is considered that the \( R(o) \) value in Fig. 1 has the same meaning as \( R(e) \) value. When the distance from the drain is known, the \( R(o) \) value and the corresponding decrease of \( R(q_u) \) can be obtained from Figs. 1 and 2, respectively.

The relationship between the \( c_0/c_w \), \( c_0/c_{(u)} \), \( c_0/c_{(u)} \) and \( R(e) \), and the \( r/r_w \) are shown in Fig. 3. In Fig. 3, \( c_0/c_w \) values are obtained by substituting \( R(q_u) \) values, which are obtained from Figs. 1 and 2, for Eq. (1). The relationships between \( c_0/c_{(u)} \), \( c_0/c_{(u)} \) and \( r/r_w \) are obtained from Figs. 1 and 2 and Eq. (1) in the same manner. The \( c_0/c_{(u)} \), \( c_0/c_{(u)} \) values are derived from \( c_0 \), \( c_{(u)} \) of disturbed sample divided by \( c_{(u)} \). In the undisturbed zone, the \( c_0/c_{(u)} \) value is about 1.70, and in the completely remolded soil in the periphery of the drain, about 0.46. The \( c_0 \) value after vertical drain piling in the ground can be obtained from \( c_0 \) value of undisturbed sample using the \( c_0/c_{(u)} \) curve in Fig. 3.

**DECREASE OF THE COEFFICIENT OF CONSOLIDATION WITH THE PROGRESS OF CONSOLIDATION**

The \( c_0 \) value of the ground improved by vertical drain becomes smaller with the progress of consolidation. It can be guessed that the degree of the retardation of consolidation differs with the sedimentary environment of soil, ground faces, etc.

The effect of the retardation of consolidation on the \( c_0 \) value is examined by the back analysis using the measured settlements of the 14 different sites, which were improved by Sand drain (SD) in Japan. The back analysis to find the \( c_0 \) value was performed by using Barron’s solution (Barron, 1948) to employ the \( n (=r/r_w) \) value of the sand drain and the reclamation load.

Figure 4 shows the correction curves for the relationships between \( c_0/c_w \) and the degree of consolidation \( (U) \), which were obtained from the measured settlement of the marine and the continental clay deposits in Japan. The solid line and broken line in Fig. 4 represents the marine and the
continental clay deposits, respectively, where \( c_{ho} \) is the coefficient of consolidation which was back analyzed with each \( U \) and \( c_{hi} \) is the coefficient of consolidation right after reclamation.

The relationships between \( c_{ho}/c_{hi} \) and \( U \) show the different tendencies between the marine and the continental clay deposits. The \( c_{ho}/c_{hi} \) values of the marine clay deposits become smaller with the progress of consolidation, about 0.4 with the \( U = 100\% \). The decrease of \( c_h \) value with the progress of consolidation on the ground improved by SD can be corrected by the curves in Fig. 4. It was confirmed in Shogaki et al. (1997) that the curves in Fig. 4 are independent on \( l_p \), natural water content \( w_c \), \( c_h \), and \( n \).

A METHOD FOR SETTLEMENT ANALYSIS TAKING INTO CONSIDERATION BOTH DISTURBANCE AND THE DECREASE OF COEFFICIENT OF CONSOLIDATION

The disturbed zone at the periphery of the drain is shared with arbitrary blocks as shown in Fig. 5 and assigned \( c_h \) derived from Fig. 3, to those blocks. The permeability for horizontal direction of the \( j \) block, \( k_{ho} \), is given by Eq. (2).

\[
k_{ho} = c_{ho} \omega_0 \quad (j = 1, 2, \ldots)
\]

where, \( m_{ho} \) is the coefficient of volume compressibility for horizontal direction of the \( j \) block. In the \( j \) block, Eq. (3) is derived in conformity with Darcy's law.

\[
v_w = c_{ho} m_{ho} \frac{\Delta h_j}{\alpha_j \beta_j \Delta r}
\]

where, \( \Delta h_j \) and \( \Delta r \) are the water head and the drainage length of the \( j \) block. Here, the relationships between \( c_{ho} \) and \( c_{ho}(u) \), \( m_{ho} \) and \( m_{ho}(u) \) is assumed to be based on the Eq. (4).

Then, Eq. (5) is derived from Eq. (3) with the consolidation parameters of the undisturbed zone.

\[
\alpha_j = \frac{c_{ho}(u)}{c_{ho}}, \quad \beta_j = \frac{m_{ho}(u)}{m_{ho}}
\]

\[
v_w = c_{ho}(u) m_{ho}(u) r_s \frac{\Delta h_j}{\alpha_j \beta_j \Delta r}
\]

Here, \( \alpha_j \) value can be the reciprocal value derived from Fig. 3. In this study, \( \beta_j \) value is assumed to be one, because the effect of soil disturbance on \( m_{ho} \) is slight. This assumption is generally permitted in view of the practical design. The effect of soil disturbance on consolidation is described as the suspected change of the drainage length with Eq. (5). When \( \alpha_j \) values are derived from all the blocks in the same manner, the effective radius, \( r_e \) of SD is given by Eq. (6).

\[
r_e = \sum_{j=1}^{n} (\alpha_j \Delta r) + r_{water}
\]
When the $r_1$ value is substituted for Barron's solution instead of the $r$ value, the settlement analysis, taking soil disturbance and the retardation of consolidation into consideration, can be performed using the consolidation parameters which were obtained before drain installation.

VALIDITY OF THE PROPOSED METHOD

The applicability of the proposed method is examined with Saitama-2 site (Koga, 1982) as the continental clay deposit and Haneda-2 (Mamyama et al., 1991) as the marine clay deposit. The predictions of settlement are performed using four different coefficient of consolidation employing the $c_v$ value before drain installation.

(a) The $c_v$ value before drain installation, which is widely used in Japan.
(b) Onoue's method (1988) which assigned the $c_v$ value before drain installation for the undisturbed zone and the $c_v$ value of remolded soil for the disturbed zone.
(c) The $c_v$ value obtained from Fig. 3.
(d) The proposed method that added the retardation of consolidation obtained from Fig. 4.

Figures 6 and 7 show the schematic picture of Saitama-2 and Haneda-2.
CONCLUSIONS

The conclusions obtained from this study are summarized as follows:

1) The relationships between anisotropy of consolidation parameters and soil disturbance after vertical drain piling in the ground are give as the function of the distance from the drain.

2) In the undisturbed zone, the ratio of the coefficient of consolidation for vertical direction to that for horizontal direction is about 1.7, and in the completely remolded zone in the periphery of the drain, about 0.5.

3) The correction curves for the retardation of the consolidation were given for both the marine and the continental clay deposits, and are independent of the soil properties and the drain placement.

4) The accuracy for the prediction of the consolidation settlement by the proposed method under $c_v=80\%$ were (7 ~ 20)$\%$ for the marine clay deposits and (3 ~ 20)$\%$ for the continental clay deposits.

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