A Study on Consolidation Behavior of Dredged Clay with Horizontal Drains

Y. S. Jang  
Dept of Civil and Environmental Engineering, Dongguk University, Seoul, Korea  
yjang@dongguk.edu

C. S. Park  
Geotechnical and Environmental Engineering Branch, Far East District, Corps of Engineers, Seoul, Korea  
csp001@hanmail.net

J. Y. Park  
Teso Engineering, Seoul, Korea  
jiban72@hanmail.net

S. S. Kim  
Dept of Civil and Environmental Engineering, Hanyang University, Ansan, Korea  
Kimss@hanyang.ac.kr

ABSTRACT: A numerical analysis method was developed to predict the consolidation behavior of very soft soil with horizontal drains under the action of the gravity pressure. Especially, seepage pressure produced at installed horizontal drains was considered in the analysis by developing a new boundary condition for drains in arbitrary arrangement. The numerical analysis for soil with horizontal drains was compared with the case of self-weight consolidation. The influence of design factors, such as a lateral spacing and a depth of installation of drains, on consolidation process was studied. As a result of analysis, it is found that the time to reach the degree of consolidation of 95% using horizontal drains takes 9 times less than that of self-weight consolidation and the whole settlement of clay with drains was occurred more than three times compared with the case without drains.

1 INTRODUCTION

In the case of offshore fill construction, marine clay that is easily obtained from offshore, is often used as dredged fill material. Since the dredged fill clay has high moisture content, high compressibility, and little strength in the initial period of self-weight consolidation, it is very difficult not only to place construction equipment, but also to walk on the surface of dredged fill. Thus, it is necessary to develop appropriate soil improvement methods stabilizing the surface layer of very soft clay in a short period of time to have trafficability for heavy construction equipment. Among these methods, the horizontal drain method by installing drains horizontally in the ground is often used to expedite the dispersion of pore water and to increase the strength of clay under the action of gravity or vacuum. This method was developed by the Penta-Pacific construction company in Japan for the first time and used for improving dredged fill in an airport construction of Kanda region, and in the waste sludge disposal of Yamakuchi region.

To stimulate the practical application of horizontal drain method and for the purpose of economic design of drains, it is necessary to develop an appropriate analysis method for predicting time-settlement behavior of dredged fill clay with drains.

Mikasa (1963) and Gibson (1967, 1981) derived the one-dimensional finite strain equation for self-weight consolidation of a saturated clay layer. Chung (1993) carried out the large scale test and the numerical analy-
sis for vacuum consolidation with vertical wick drains. Kim et al. (1995) studied numerical analysis of
dredged fill clay with horizontal drains based on the consolidation theory suggested by Mikasa (1963). Kim
(1998) performed a numerical study on dredged soft clay with horizontal drains installed in square pattern ar-
rangement. Lee et al. (2001) performed numerical and laboratory studies on the horizontal drain method under
the action of vacuum pressure.

In this study a numerical analysis method was developed to predict the consolidation behavior of very soft
soil with horizontal drains under the action of the gravity pressure. Especially, two simultaneous consolidation
processes such as self-weight consolidation and three-dimensional consolidation by seepage pressure around
horizontal drains were considered in the analysis by developing a new boundary condition for drains installed
in arbitrary arrangement. A finite differential method based on Dufort-Frankel method was used for the analy-
sis.

To analyze the effect of horizontal drains, a numerical analysis for horizontal drains under the action of
gravity was compared with that of self-weight consolidation only. The influence of design factors, such as a
lateral spacing and a depth of installation of drains, on consolidation process was studied.

2 THEORY OF FINITE STRAIN CONSOLIDATION FOR HORIZONTAL DRAIN METHOD

In horizontal drain method under the action of gravity force, drains are installed horizontally in the ground
to flow pore water out from ends of drains by pumps to expedite the dispersion of water as shown in Figure 1.

\[ (\gamma_s - \gamma_w)g\lambda + g \frac{\partial e^2}{\partial z^2} = \frac{\partial e}{\partial t} \]  

(1)

where \( e \) is a void ratio, \( z \) is a reduced coordinate, \( g \) is a finite strain coefficient of consolidation, \( \lambda \) is a lin-
earization constant, \( \gamma_s \) is a unit weight of solids, and \( \gamma_w \) is a unit weight of pore water.

In equation (1), \( \lambda \) and \( g \) is expressed as follows:

\[ \lambda = \frac{d}{de} \left( \frac{de}{d\sigma'} \right) \]  

(2)

\[ g = \frac{k(e) 1}{\gamma_w} \frac{d\sigma'_e}{1 + e \frac{de}{d\sigma'}} \]  

(3)
The equation (1) can be expanded to completely uncoupled three dimensional governing equation of the finite strain consolidation as follows (Chung, 1993):

\[
\frac{de}{dt} = (\gamma_s - \gamma_w) g \frac{\partial e}{\partial z} + g \frac{\partial e^2}{\partial z^2} + \frac{(1 + e_0)}{\gamma_w \lambda} \left[ \frac{1}{e - e_\infty} \frac{dk(e)}{dx} \frac{de}{dx} - \frac{k(e)}{(e - e_\infty)^2} \left( \frac{de}{dx} \right)^2 + \frac{k(e)}{(e - e_\infty)^2} \frac{d^2 e}{dx^2} \right] \\
+ \frac{(1 + e_0)}{\gamma_w \lambda} \left[ \frac{1}{e - e_\infty} \frac{dk(e)}{dy} \frac{de}{dy} - \frac{k(e)}{(e - e_\infty)^2} \left( \frac{de}{dy} \right)^2 + \frac{k(e)}{(e - e_\infty)^2} \frac{d^2 e}{dy^2} \right] 
\]

where \( e_0 \) is an initial void ratio, \( e_\infty \) is a void ratio at the completion of consolidation, and \( k \) is a coefficient of permeability.

2.2 Problem Characterization

Typical arrangement of horizontal drains is shown in Figure 2(a). Drains are assumed to be installed arbitrarily at any point of a cross-section of soil. A soil element with six boundaries is selected for analysis as shown in Fig. 2(b). 

![Cross-section of horizontal drains](image1)

![Boundaries of a soil element](image2)

Figure 2. Schematic diagram of a soil element with horizontal drains in clay

2.2.1 Initial Condition

Assuming that void ratio at any points of clay right after completing a fill has the same value, an initial void ratio through the soil layer at initial stage \((t=0)\) can be described by the following equation.

\[ e(x, y, z)_{t=0} = e_{00} \]  

where \( e_{00} \) is an initial void ratio.

2.2.2 Boundary Conditions

The void ratio at the upper surface is assumed constant through consolidation stage by neglecting the effect of desiccation as follows:

\[ e(x, y, z) = e_{00} \]  

The front, right, left, and back sides are assumed as impervious boundaries. Referring Figure 2(b), the boundary conditions require
Using an equation of equilibrium of water and solid mixture in the soil and the modified Darcy’s law, an impervious condition at the lower boundary ($z=1$) can be expressed as follows:

$$\frac{\partial e(x, y, z)}{\partial z} = -\lambda (\gamma_s - \gamma_w)(e - e_n)$$

2.3 Boundary Condition for Horizontal Drains

It is assumed that the water pressure at the ends of drain keeps zero by pumping the extracted water from drain and the coefficient of permeability in drain is infinite. Then, the immediate increase of effective stress at drain will be produced by the action of seepage pressure after installing drain. The increase of effective stress is the sum of that of self-weight of soil particles ($\gamma_s z_n$) and that of water pressure ($\gamma_w z_n e_n$) as shown in Figure 3.

![Figure 3. Increase of effective stress at horizontal drain by seepage pressure](image)

Therefore, the boundary condition of the drains installed in arbitrary points becomes

$$e(x_n, y_n, z_n) = (e_{00} - e_n) \exp[-\lambda (\gamma_s + e_{00} \cdot \gamma_w) z_n] + e_v$$

where $x_n$ and $z_n$ are coordinates of each drain installed.

2.4 Finite Difference Equation for Numerical Analysis

An Explicit Dufort-Frankel finite differential method is applied to the governing equation (4) as follows:

$$E^{T+\Delta T} (x_i, y_j, z_k) = (1/C_i)\{C_2 E^{T-\Delta T} (x_i, y_j, z_k) $$

$$+ C_4 E^T ((x_i + \Delta x, y_j, z_k) + C_4 E^T ((x_i - \Delta x, y_j, z_k)$$

309
\[ + C_z E^T ((x_i, y_j + \Delta y, z_k)) + C_0 E^T ((x_i, y_j - \Delta y, z_k)) \\
+ C_y E^T ((x_i, y_j, z_k + \Delta z)) + C_y E^T ((x_i, y_j, z_k - \Delta z)) \\
- C_0 [E^T ((x_i + \Delta x, y_j, z_k)) - E^T ((x_i + \Delta x, y_j, z_k))]^2 \\
- C_{10} [E^T ((x_i, y_j + \Delta y, z_k)) - E^T ((x_i, y_j - \Delta y, z_k))]^2 \] 

(13)

3 ANALYSIS OF CONSOLIDATION EFFECT BY HORIZONTAL DRAINS

3.1 Comparison of Self-Weight Consolidation and Horizontal Drain Method

To analyze the effect of accelerating consolidation by using horizontal drains, a numerical analysis result for horizontal drains under the action of gravity was compared with that of only self-weight consolidation. Input data for a numerical analysis are summarized in Table 1. The arrangement of horizontal drains installed is shown in Figure 4.

<table>
<thead>
<tr>
<th>Initial height of soil layer ( h_0 (\text{m}) )</th>
<th>Unit weight of solid ( r_s (\text{kN/m}^3) )</th>
<th>Initial water content ( w_0 (%) )</th>
<th>Initial void ratio ( e_{00} )</th>
<th>Final void ratio ( e_{\infty} )</th>
<th>Finite strain coefficient of consolidation ( g (\text{m}^2/\text{day}) )</th>
<th>Liberalization constant ( A (\text{m}^2/\text{kN}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>26.7</td>
<td>220</td>
<td>5.874</td>
<td>0.772</td>
<td>0.01</td>
<td>0.087</td>
</tr>
</tbody>
</table>

Table 1. Input data for a numerical analysis

Plot for settlement versus time for self-weight consolidation and horizontal drain method is represented in Figure 5. The time to reach the degree of consolidation of 95\% using horizontal drains takes 9 times less than that of self-weight consolidation. The final settlement using horizontal drains is about 3 times greater than that of self-weight consolidation. It is shown that horizontal drains can be an effective method for accelerating consolidation of soft clay by extruding pore water horizontally through drains.

The distributions of void ratio with the variation of time at \( x=0.25 \text{m} \) for self-weight consolidation and horizontal drain method are represented in Figure 6. In this Figure the vertical axis means normalized non-dimensional reduced coordinate. It is noted that in the case of horizontal drain method the void ratio at drains decreases rapidly at the initial stage of consolidation and those at other points decrease with the change of time. However, in the case of self-weight consolidation, the void ratio decreases with time from the bottom side of the soil as shown in Figure 6 (a).
3.2 Analysis of Consolidation Effect with Various Design Factors for Drains

To accelerate consolidation process in clay with horizontal drains, the effective design is necessary. The influence of various design factors such as a lateral spacing and a depth of installation of horizontal drains on consolidation behavior are analyzed.

3.2.1 Influence of a lateral spacing of installation

Numerical analysis results of horizontal drains with the variation of the lateral spacing of 0.3, 0.5, 1.0, and 2.0m are shown in Figure 7 assuming the soil depth as 1m. It is shown that the consolidation of the clay can be accelerated faster with the shorter spacing of drains. However, the difference of consolidation process between the drain spacing of 0.3m and 0.5m is not much. It seems that the spacing of 0.5m may be optimum to flow out pore water for this specific case. So, it is necessary to determine an appropriate spacing of drains by reiterating calculation.

3.2.2 Influence of installation depth

Figure 8 shows the cross section of numerical model performed for horizontal drains with drain installation depths of 0.5, 1.5, and 2.5m. Figure 9 shows the void ratio with the change of installation depth of drain. It is found that void ratio near drains decreases faster in the initial stage of consolidation when drains are installed in lower location due to the increase of seepage pressure. This initial decrease of void ratio results in accelerating the consolidation process. Therefore, the effectiveness of horizontal drain method increases in reducing consolidation time as drains are installed in lower place.
3.2.3 Influence of installation number of drain layers

The influence of the number of installation layers of horizontal drains on consolidation process is analyzed for the three cases of drain layers as shown in Figure 10. Plots of time versus settlement are shown in Figure 11. It is shown that both of the whole settlement of soil and the rate of settlement increase as the number of installation of drains increase.
4 CONCLUSIONS

(1) A numerical analysis method was developed to predict the consolidation behavior of very soft soil with horizontal drains under the action of the gravity pressure.

(2) The time to reach the degree of consolidation of 95% using horizontal drains takes 9 times less than that of self-weight consolidation. The final settlement using horizontal drains is about 3 times greater than that without drains. It is shown that horizontal drain can be an effective method for accelerating consolidation of shallow soft clay by producing seepage pressure at drains.

(3) It is found that void ratio at drains decrease more in the initial stage of consolidation when drains are installed in lower location due to the increase of seepage pressure. Effectiveness of horizontal drain method increases in reducing consolidation time as drains are installed in lower place.

(4) Increase in the number of installation layers of drains vertically is more effective than the decrease in the lateral spacing for optimal design of drains if same number of drains can be used.

REFERENCES


