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Abstract

Columnar inclusion is one of the effective and widely used methods for improving engineering properties of soft clay ground. This paper investigates the consolidation behavior of composite soft clay ground using both physical model tests under an axial-symmetry condition and finite element simulations using the PLAXIS 2D program. Because the soil-cement column enhances the yield stress and stiffness of the composite ground, the composite ground is in an over-consolidated state under the applied vertical applied stresses. At this state, the rate of consolidation is rapid due to a high coefficient of consolidation. The consolidation of the composite ground is mainly controlled by the area ratio, the ratio of the diameter of the soil-cement column to the diameter of the composite ground, a . As the area ratio increases, the rate of consolidation increases and the final settlement decreases.

Keywords

soft, composite, behavior, consolidation, ground, analysis, finite, element

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Finite Element Analysis of Consolidation Behavior of Composite Soft Ground

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ABSTRACT

Columnar inclusion is one of the effective and widely used methods for improving engineering properties of soft clay ground. This paper investigates the consolidation behavior of composite soft clay ground using both physical model tests under an axial-symmetry condition and finite element simulations using the PLAXIS 2D program. Because the soil-cement column enhances the yield stress and stiffness of the composite ground, the composite ground is in an over-consolidated state under the applied vertical applied stresses. At this state, the rate of consolidation is rapid due to a high coefficient of consolidation. The consolidation of the composite ground is mainly controlled by the area ratio, the ratio of the diameter of the soil-cement column to the diameter of the composite ground, a . As the area ratio increases, the rate of consolidation increases and the final settlement decreases.

INTRODUCTION

The method of mixing cement slurry or powder into soft ground (deep mixing) to create soil-cement columns is widely used to improve the engineering properties (shear strength and compressibility) of thick deposits of soft ground. Studies on the prediction of the engineering performance of soil-cement column improved ground have become attractive to both practitioners and researchers in Asia. Most of the available studies related to the deep mixing method have been confined to the strength and the overall stiffness of the soil-cement columns (Kawasaki et al., 1981; Kamaluddin and Balasubramaniam, 1995; Porbaha et al., 2001; Miura et al., 2001; Horpibulsuk et al., 2004a, b; 2005; 2011a and b). The effect of the field mixing parameters, such as installation rate, water/cement ratio and rate of rotation on the strength development of soil-cement columns were investigated by Nishida et al. (1996) and Horpibulsuk et al. (2004c and 2011b). Based on the available compression and shear test results, many constitutive models were developed to describe the engineering behavior of cemented clay (Kasama et al., 2000; Horpibulsuk et al., 2010; Suebsuk et al., 2010 and 2011 etc).

Even though the understanding of the consolidation behavior of composite ground is significant for determining the final settlement and rate of settlement, the studies on this topic are very limited. This paper aims to illustrate the consolidation

mechanism of the composite ground. Both laboratory tests on model composite ground and numerical simulations were performed for this objective. The laboratory tests were carried out in different conditions of the applied vertical stress and area ratio, which is the ratio of the soil-cement column diameter to the composite ground diameter. Numerical simulations were performed using the PLAXIS program.

SOIL SAMPLE AND PHYSICAL MODEL

The soil sample was soft Bangkok clay collected from the Chidlom district, Bangkok at a depth of three meters. The clay was composed of 11% sand, 17% silt and 72% clay. The natural water content was 80% and the specific gravity was 2.68. The liquid and plastic limits were 81% and 34%, respectively.

Figure 1. Location of instruments in the physical model: (a) plan view of positions of various transducers; (b) side view.

A cylindrical stainless steel mold 300 mm in diameter and 450 mm in height was used for the experimental research as shown in Figure 1. The soil-cement columns with 5 cm and 10 cm diameters were installed in the middle of the mold. This physical model test simulated a composite foundation where soil-cement columns are installed vertically in a triangular or square pattern at the same spacing in a horizontal clay layer and are subjected to uniform vertical fill loading over an extensive area (Yin and Fang, 2006). The consolidation around a soil-cement column was approximately axisymmetrical with an equivalent diameter, at the boundary of which lateral displacement was not permitted. The concept of the equivalent diameter is first introduced by Barron et al. (1948) to study the consolidation behavior of soil cylinder containing a central sand drain. The vertical load on the model ground was applied by dead weights on a level hanger.

NUMERICAL ANALYSIS

The performance of the composite ground (prior to column failure) was simulated using the PLAXIS 2D program and the simulations were compared with the test results to understand the consolidation mechanism of the composite ground and to understand the role of area ratio, a on the consolidation behavior. The finite element mesh was composed of 15-nodes triangular elements (*vide* Figure 2). The load was applied by step loading; the next loading was applied after the consolidation that was caused by the previous loading was complete. The applied load was 0, 20, 40 and 60 kPa. Table 1 shows the model parameters for the surrounding clay and the soil-cement column. All the model parameters were obtained from the conventional laboratory tests. Overall, the numerical simulations are comparable with the test results.

Figure 2. Finite element model for the model composite ground.

Table 1. Model parameters for the composite ground.

Soil	Sand	Bangkok clay	Soil-cement column	Unit
Model	Mohr-Coulomb	Soft Soil	Mohr-Coulomb	-
γ_{dry}	17	16	13 (C = 20%) 14 (C = 40%)	kN/m ³
γ_{sat}	20	18	13 (C = 20%) 14 (C = 40%)	kN/m ³
k_v	3.43×10^{-4}	1.0×10^{-7}	5.0×10^{-6}	m/min
k_h	3.43×10^{-4}	1.0×10^{-7}	5.0×10^{-6}	m/min
E'	13,000 (Top) 52,000 (Bottom)	-	112,000 (C = 20%) 120,000 (C = 40%)	kPa
ν'	0.3	0.3	0.3	-
λ^*	-	0.095	-	-
K^*	-	0.0095	-	-
c'	1	1	600	kPa
ϕ'	37	21	25	degrees

Figure 3. Comparison between simulated and measured settlement with time for different area ratios and cement contents.

Figure 3 shows the comparison between the simulated and measured settlements versus time for different area ratios, a . Both the settlement and rate of consolidation are governed by a . The composite ground with a high a value exhibits low settlement and a high rate of consolidation. Figure 4 depicts the change in the excess pore pressure with radial distance at different consolidation times for the vertical stress increased from 20 kPa to 40 kPa. The excess pore pressures in the soil-

cement column dissipate more quickly than those in the surrounding clay only at the top of the composite ground; the excess pore pressures in both the soil-cement column and the surrounding clay at the same consolidation time are practically the same for deeper improvement depths.

Figure 4. Relationship between simulated excess pore pressure and radial distance at different times and area ratios.

As the area ratio increases, the stiffness/composite area and the yield stress of the composite ground increases. Consequently, the rate of consolidation increases and final settlement decreases for a given applied load. The yield stress of the composite ground can be determined in the same way as that of the soft clay in conventional consolidation test.

Figure 5 shows the typical relationship between the excess pore pressure and depth at different consolidation times. The consolidation behavior of the surrounding clay for the points near and far away from the soil-cement column (at 5 and 10 cm from the column) is similar to that of the clay deposit without soil-cement column. The maximum excess pore pressure is at the bottom and decreases with consolidation time. The rate of consolidation of the soft clay (no column) is slower and mainly dependent upon the coefficient of permeability. The soil-cement column enhances overall stiffness of the composite ground and hence the coefficient of consolidation.

The composite coefficient of consolidation ($c_v = \frac{k}{\gamma_w m_v}$) increases due to the increase in m_v , even though the permeability of both the surrounding clay and the column are almost the same.

Figure 5. Relationship between excess pore pressure and depth at different consolidation times for $a = 1/6$.

CONCLUSIONS

This paper presents the numerical simulation of the consolidation behavior of composite ground. The coefficients of permeability of the soil-cement column and surrounding clay are practically the same; therefore the soil-cement column does not act as the drain. Because the soil-cement column enhances the yield stress and stiffness of the composite ground, the composite ground is in an over-consolidated state under the applied vertical applied stresses. At this state, the rate of consolidation is rapid due to a high coefficient of consolidation. The area ratio, a , significantly affects the consolidation behavior of the composite ground. The composite ground

with a high a value has a high load capacity and carries low stress. Thus, the settlement is small and consolidation is rapid.

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