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Behaviors of Soil-cement Piles in Soft Ground

연약지반에 설치된 소일시멘트말뚝의 거동

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요 지

복합기초의 한 형식인 소일시멘트 말뚝의 거동 특성을 컴퓨터 해석을 통하여 연구하였다. 연직하중을 받는 소일시멘트말뚝의 거동 특성을 ABAQUS라는 상용 프로그램을 사용하여 조사하였으며 해석조건은 지반물성치, 말뚝의 길이, 치환율, 강성비, 하중 조건 등을 달리하여 실시하였다. 해석 결과는 하중의 전이 및 침하특성 뿐만 아니라 효과적인 말뚝길이와 말뚝 및 지반의 하중 분배에 관하여서도 유용하게 쓰일 수 있음이 판명되었다. 또한 복합기초를 설계할 때 강성비, 치환율이 설계에 가장 큰 영향을 미치는 인자로 나타났다.

Abstract

This study was undertaken to investigate behavior characteristics of soil-cement piles in composite foundations through computer analysis. The soil-cement piles with cushion subjected to the vertical central loading only were analyzed using the program - "ABAQUS". The investigation was conducted for various conditions including soil property, pile dimension, replacement ratio, pile/soil modular ratio, and load intensity. The results of analysis provided not only the load transfer and settlement behaviors but also the effective pile length and load distribution between a pile and soil. It was concluded that in the design of composite foundations, the modular ratio and replacement ratio are two design parameters.

Keywords : ABAQUS, Replacement ratio, Soft ground, Soil-cement piles

1. Introduction

The population growth has caused many engineering activities on soft ground. Many techniques have been developed to improve a soft ground with insufficient shear strength. The available techniques for soft ground improvement include compaction, stabilization, replacement, consolidation, and reinforcement to name a few (ASCE, 1978 and 1987). Although ground reinforcement can be accomplished either vertically or horizontally, the vertical reinforcement method is more popularly used because of easier installation of vertical reinforcing materials than horizontal reinforcing materials.

Among the various vertical-reinforcing techniques for soft ground improvement, reinforcing elements using cast-in-place piles have received remarkable attention in the last three decades. The piles can be constructed with different materials, such as stone or gravel with or without Portland cement, sand mixed with Portland cement, local soil stabilized with lime or Portland

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cement, and others. The selection of a suitable material greatly depends upon the existing ground conditions, material availability, and cost.

A layer of cushion is installed between the top of piles and the base of footing; the cushion provides a better contact between the footing and the ground surface which results in spreading the footing pressure more uniformly to the top of pile and the surrounding soil. The cushion layer is normally constructed with a local coarse-grained material with or without stabilization.

The cast-in-place piles together with the cushion and the soft ground form a composite foundation, which supports the overlying structure. Currently, there are design methods developed for some specific materials/ loading conditions. However, there is not yet a widely accepted rational design method for such a foundation system. For the development of a widely accepted design method, the behavior of load transfer through the cushion layer and the pile needs to be understood thoroughly. This paper presents the results of a study on the load transfer and settlement behaviors of soil-cement piles subjected to vertical central loading.

2. Conditions of Analysis

The analyses were undertaken using a commercially available finite element program named ABAQUS. The program was developed based on a number of failure/ yield criteria for 2D and 3D elastic and/or elasto-plastic analyses (ABAQUS, 1996). In the analysis, the soil-cement piles were considered elastic while the surrounding soils were treated as elasto-plastic materials, which obey the Drucker-Prager yield criterion. Because of the triangular pattern of pile location layout, the analysis was made for a single pile with axi-symmetrical loading and boundary conditions which is shown in Fig. 1. The axi-symmetrical finite element mesh was composed of quadrilateral elements having an axi-symmetrical boundary at its left vertical face. The right vertical boundary and bottom horizontal boundary were composed of the infinite elements. A uniform vertical pressure loading was applied at the top of the cushion elements. The total number of elements for a typical mesh was about 360. The meshes were generated so that the ratio of the vertical and horizontal extensions may be less than 1 to 4.

The analyses were performed for various conditions including loading intensities, material properties, pile

Table 1. Physical properties

Items			Assumed Values
Load (kPa)			50, 100, 150, 200, 300, 400
pile		Length (m)	5, 8, 11
		Diameter (m)	0.3, 0.4, 0.5
		Replacement Ratio	0.0816, 0.145, 0.227
		Elastic modulus (MPa)	325, 650, 1300, 3250
		Poisson's ratio	0.20
Cushion		Thickness (m)	0.2
		Elastic modulus (MPa)	400
Soil	Top 8m	Elastic modulus (MPa)	65
		Yield parameter(β)	30.0°
		Yield parameter(κ)	0.9
		Yield parameter(Ψ)	0.0
	Bottom	Elastic modulus (MPa)	90
		Yield parameter(β)	30.0°
		Yield parameter(κ)	0.9
		Yield parameter(Ψ)	0

$$\beta = \tan^{-1}\frac{6\sin\phi}{2-\sin\phi},\quad x = \frac{3-\sin\phi}{3+\sin\phi},\quad \phi = 20^\circ$$

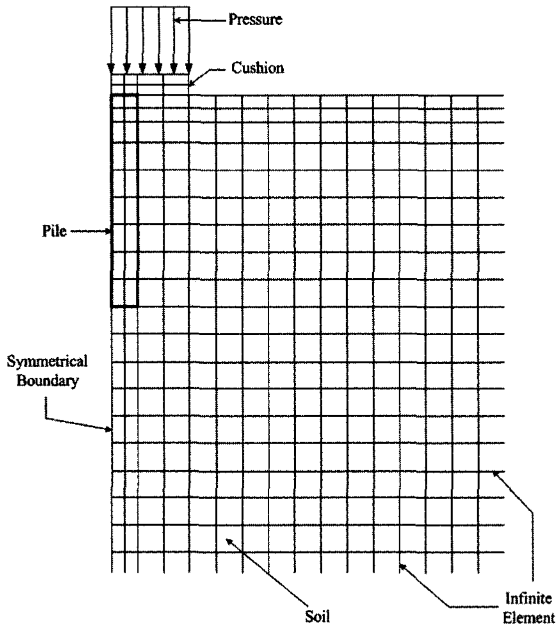

Fig. 1. Schematic diagram of numerical model

dimensions (length and diameter), and pile spacing. Note that, in the analysis, the pile spacing is also expressed in terms of replacement ratio, which is the ratio between cross section areas of pile and cushion. The diameter of cushion equals the center-to-center pile spacing. The conditions analyzed are summarized in Table 1.

3. Settlement Behavior

Settlement of pile varies with load intensity, cushion layer thickness and property, pile material and soil properties, replacement ratio, and pile length. For an 8-m long pile with a replacement ratio of 0.145 and 0.227, the variation of pile settlement with load intensity and the modular ratio between pile material and the surrounding soil is shown in Fig. 2. It shows that as the pile-to-soil modular ratio decreases, the total settlement and the rate of settlement under a load intensity increase. The greater pile settlement for a smaller modular ratio can be attributed to the greater compression which is taken place within the pile. Fig. 2 also shows that under a constant modular ratio of 10, pile settlement decreases as the replacement ratio increases. A possible explanation is that piles with higher replacement ratios have larger diameter, and have greater load resistance. Thus, under the same loading, pile settlement decreases as replacement ratios increase.

Under a given cushion material and thickness, the effect of pile length on pile settlement varies with modular ratio and replacement ratio. Results of the analyses are presented graphically in Fig. 3. Fig. 3 shows that settlement occurring in the long pile is less than that in the short piles if other factors are equal. A possible reason is that shorter piles transmit more loads to the underlying soil, causing greater soil compression which causes pile settlement. As a consequence, shorter piles settle better than longer piles. For piles with the same pile length and replacement ratio, increasing modular ratio decreases pile settlement. This is primarily due to the smaller pile compression for piles with the higher modular ratio.

4. Load Transfer Behavior

Loading at foundation induces stresses and strains in

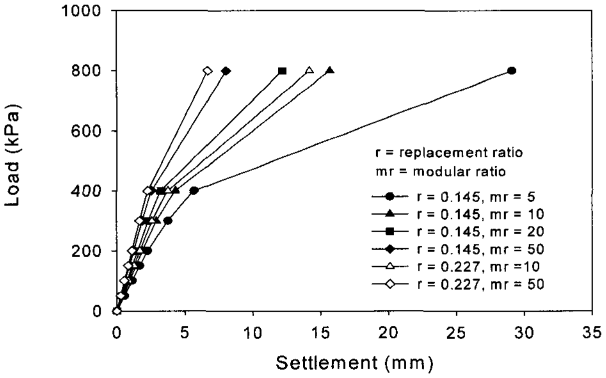

Fig. 2. Load vs. Settlement for different modular ratios and replacement ratios

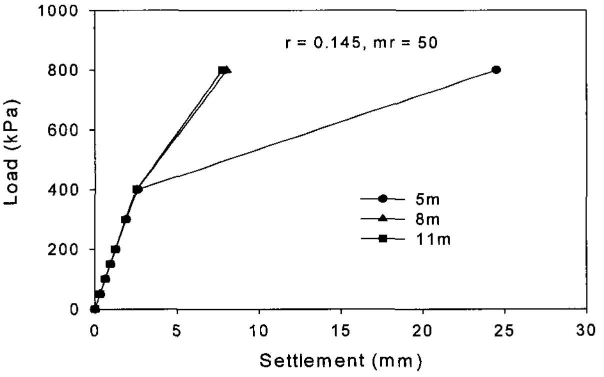

Fig. 3. Effect of pile length on settlement

the pile and the surrounding soil. The load transfer behavior can be evaluated based on the stress distribution in the pile as well as in the soil. Because of the shearing resistance mobilized along the pile/soil interface, the vertical normal stress in the pile decreases with depth except near the top portion of the pile for some cases. Within the top 1 m for piles with a greater modular ratio, the normal stress in the pile increases with depth as

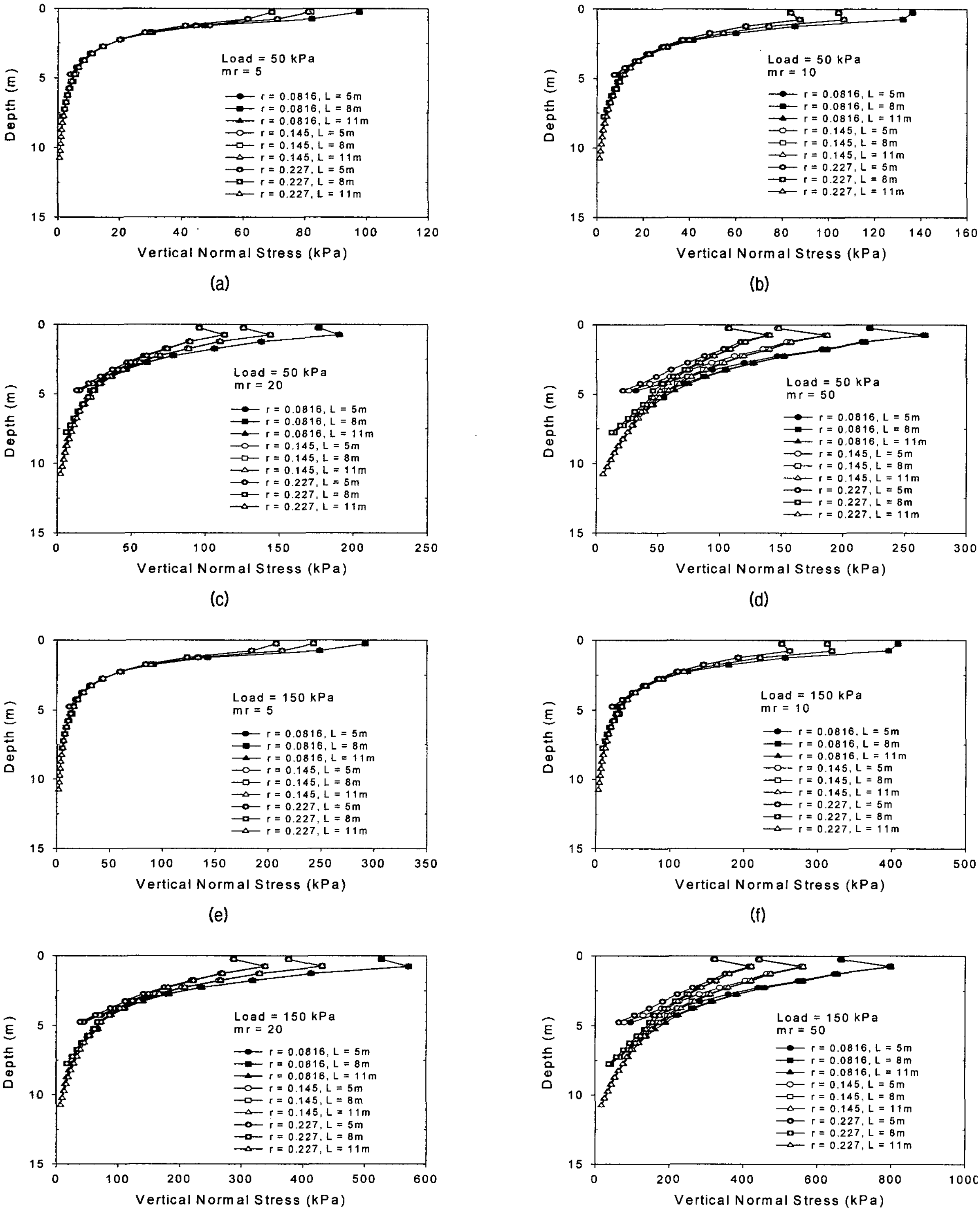

Fig. 4. Variation of vertical normal stress with depth

demonstrated in Fig. 4. Such a distribution of vertical pile stress with depth may be attributed to the possible downward shearing stress that mobilized along the pile/soil interface caused by the greater compression in the soil than in the pile. The downward shearing stress results in the increased vertical pile stress with depth.

Fig. 4 also shows the vertical stress in the pile. The distribution curves for different pile lengths and replacement ratios merge together from a depth of about 2 m for a modular ratio of 5. As the modular ratio increases, the stress distribution curves gradually move apart. At a modular ratio of 50, the curves are essentially separated each other as shown in Fig. 4(d and h). A comparison between Figs. 4(a) and (d) also show that the vertical stress in the pils increases as modular ratios for a given replacement ratio and load intensity increase. For piles with the same modular ratios, however, the vertical pile stress increases as the replacement ratio decreases.

Another view of load transfer behavior is the distribution of the ratio between the vertical normal stress in the pile and that in the adjacent soil. This ratio is also termed as stress concentration factor by Bachus and Barksdale (1989). For a replacement ratio of 0.145 and a foundation loading of 200 kPa, the variation of stress ratio with depth is shown in Fig. 5 for different pile lengths and modular ratios. The data given in the Fig. 5 show that both the magnitude and the rate of stress ratio vary with depth. As shown in Fig. 5, the stress ratio varies with depth so that it first increases to a maximum value, stays almost constant over a pile length, then decreases at the bottom portion of the pile. The bottom portion of the curve for the 11-m long pile has different shape from that of the curves for the 5-m and 8-m piles, primarily because the 11-m pile penetrates into the bottom soil layer, which extends from 8-m down and has different properties from those of the top soil layer.

Such a variation in stress ratio with depth can be explained as following. Around the top of pile, where the stress ratio increases with depth, a considerable portion of the foundation loading is transmitted directly to the soil underneath the cushion due to the flexible nature of the cushion layer. This causes soil compression as well as load transfer to the pile. As a result, the vertical stress in the pile increases. Thus, as depth increases, the vertical stress in the pile becomes greater, while that in the soil becomes smaller resulting in the increased stress ratio with depth. Near the bottom, the decreasing stress ratio with depth could be caused by boundary effect at the bottom of pile, where possible plastic yielding may alter the state of stress causing a greater rate of stress increase in the soil than in the pile. Fig. 5 also shows that stress

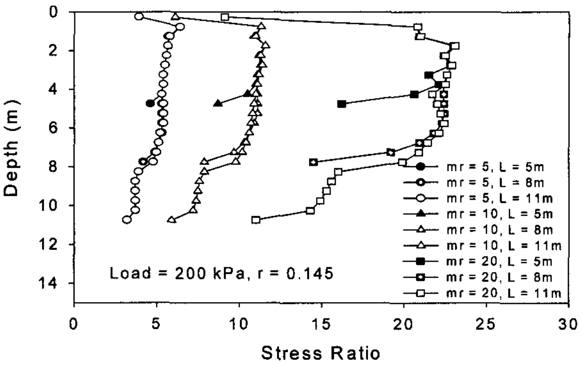

Fig. 5. Variation of stress ratio for different pile length and modular ratios with depth

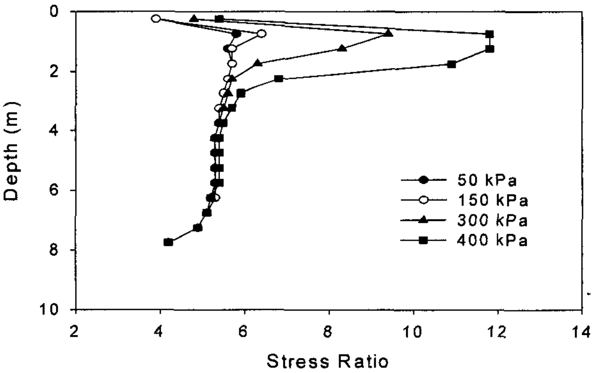

Fig. 6. Variation of stress ratios for different load with depth

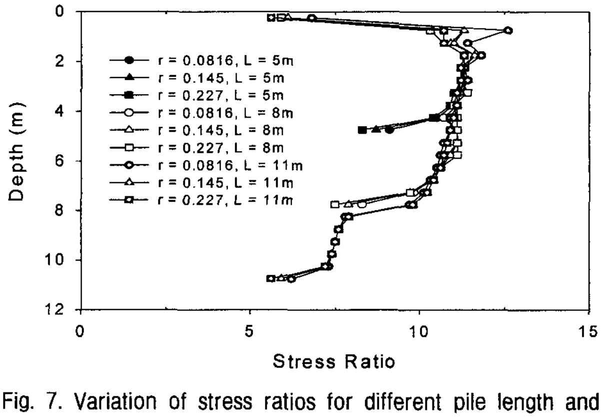

Fig. 7. Variation of stress ratios for different pile length and replacement ratios with depth

ratio varies greatly with modular ratio. This is can be expected, because stiffer piles can carry more load and thus transfer less load to the adjacent soil. As the loading increases, with other factors being equal, the stress ratio also increases but only to a depth as illustrated in Fig. 6.

The depth of influence appears to increase with loading. For the conditions of different replacement ratios, the stress ratio distributions shown in Fig. 7 are essentially the same within the range of replacement ratios analyzed. According to these data, the effect of replacement ratio on the load transfer behavior of the soil-cement piles is much less than those of the other factors investigated.

5. Effective Pile Length

It has been shown that pile performance is influenced by the pile length. However, the degree of influence is not linearly proportional to the pile length. There is a range of the pile length beyond which the degree of influence is less significant. Therefore, it is possible to determine a pile length that is economical and also satisfies the desired pile performance. Such a pile length is herein termed as the effective pile length.

The effective pile length is estimated based on vertical normal stress distribution in the pile. The load-induced normal stress in the pile is strongly related with the ultimate load capacity of pile and pile settlement. According to Sowers(1979), when the load-induced vertical stress in the ground is limited to about 10% of the vertical geostatic stress, the foundation settlement will be most likely within a tolerable range. Based on this criterion, the effective pile length is determined from the depth at which the vertical stress in the pile equals 10% vertical geostatic stress. The results of determination are presented in Fig. 8.

Fig. 8 shows that the effective pile length varies considerably with the load intensity and modular ratio. The effective pile length increases as load intensity increases due to the increased vertical stress in the pile. Meanwhile, for piles with higher modular ratios, a higher percentage of foundation load is transmitted through the pile. This causes an increase in the vertical stress, resulting in an increase in the effective pile length. The influence of replacement ratio on the effective pile length is insignificant as revealed by Fig. 7, which shows little variation in the vertical stress with the replacement ratio.

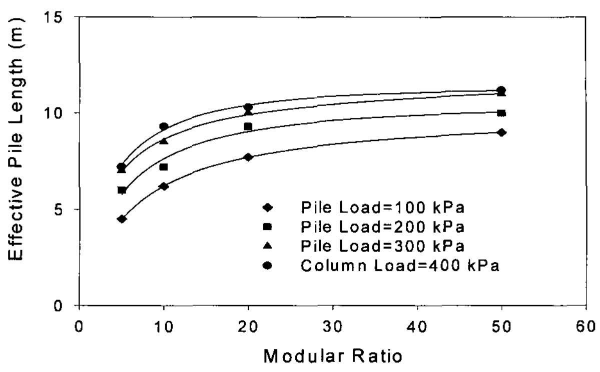

Fig. 8. Effective pile length vs. modular ratio

According to Fig. 8, the effective pile length increases with increasing modular ratio at a decreasing rate and remains almost constant at a modular ratio of about 30. The rate of change in the effective pile length with loading also decreases with increasing load intensity. The results in Fig. 8 provide a useful database for determination of effective pile length for different conditions of loading and modular ratio.

6. Summary and Conclusions

The settlement and the load transfer behaviors of soil-cement piles in a composite foundation were investigated. The study incorporated the numerical analysis, which was peformed by ABAQUS. In the analysis, the soil-cement piles were modeled to be elastic and the surrounding soil was modeled to be an elasto-plastic material with Drucker-Prager yield criterion. Various factors such as pile length, modular ratio and replacement ratio were investigated in the parametric study. From the results of analyses, the settlement and the load transfer behaviors of the soil-cement piles were evaluated. Meanwhile, the effective pile length as well as the load distribution between pile and soil was determined.

Based on the results of this study, it is concluded that the modular ratio is a key design parameter which governs the pile behavior of the soil-cement pile system. The replacement ratio is also an important design parameter, which should be properly determined to have the vertical pile stress within the allowable limit. Furthermore, the pile length should be determined with the effective pile-length principle in order to make an efficient design of the composite foundation system.

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