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Design and analyses of floating stone columns

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Abstract

Two-dimensional (2D) finite element analyses were performed on floating stone columns using the unit cell concept to investigate the settlement and the consolidation characteristics of an improved foundation system. Undrained analyses, followed by consolidation analyses, were conducted throughout the study. The computed values for settlement and excess pore pressure distribution over time are compared for different area replacement ratios. Based on these coupled consolidation analyses, a simple approximate method is developed to predict the degree of consolidation for floating stone columns. In addition, a simple method to calculate the settlement improvement factor for floating columns is proposed. The proposed method may provide more realistic answers than other design methods in view of the yielding characteristics and the influence of key parameters that are considered in the analyses. The key parameters relevant to the design of floating stone columns include the area replacement ratio, the friction angle of the column material, the loading intensity, and the post-installation earth pressure. Closer agreements are obtained with the proposed method than with the established Priebe's method or α–β method.

Keywords: Floating stone column; Unit cell; Numerical analysis; Consolidation; Settlement improvement factor

1. Introduction

Ground improvement with stone columns is effective for reducing the settlement and for increasing the time rate of the consolidation of soft soil. End-bearing columns are mostly used in design, but occasionally floating columns are adopted mostly due to construction costs and machine depth limitations (Fig. 1). Current design methods to predict the reduction in settlement and the primary consolidation of stone column reinforced grounds employ the end-bearing type of columns, e.g., Balaam and Booker (1985), Barksdale and Bachus (1983), Priebe (1995), Han and Ye (2001), Deb (2008), Castro and Sagaseta (2009) and Maheshwari and Khatri (2012). Among all the methods, the semi-empirical method proposed by Priebe (1995) is probably the most popular design method for estimating the settlement of stone column reinforced grounds. Priebe's method is based on the unit cell concept and the columns are considered to be in a plastic state, while the surrounding soil behaves elastically. The solution is given as a settlement improvement factor, n, defined as the ratio of the final settlement with and without columns. The basic improvement factor, n_0, is derived from the assumption that the columns possess an infinite modulus of elasticity. A correction to this assumption is made by considering the compressibility of the columns with a more realistic value, and this yields a reduced improvement factor,

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Nomenclature

c'	effective stress cohesion
c_{v1}'	average vertical coefficient of consolidation
d	drainage path
k	coefficient of permeability
m	modular ratio
n	settlement improvement factor
n_s	stress concentration ratio
q	loading intensity
r_c	radius of column
r_e	radius of influence area
s	settlement
u	pore water pressure
t	time
ν	Poisson's ratio
D	diameter of stone column
D_e	equivalent influence of diameter
D_c	constraint modulus of column
D_s	constraint modulus of soil
D_{comp}	constraint modulus of composite soil
E_c	Young's modulus of column
E_s	Young's modulus of soil
H_C	thickness of the part of the treated zone to be regarded as an untreated zone
K	earth pressure coefficient
H_L	length of stone column
H_1	thickness of improved layer
H_2	thickness of unimproved layer
N	diameter ratio
T_v	time factor in vertical flow
T_v'	modified time factor in vertical flow
U	average degree of consolidation
α	area replacement ratio
β	depth ratio
ϕ_c'	stone column's effective friction angle
ϕ_s'	soil's effective friction angle
γ	unit weight
ψ	dilation angle
Δu	excess pore water pressure

n_1. The final improvement factor, n_2, takes into account the variations in stress with depth which are ignored during the initial formulation of n_0.

The design for floating stone columns currently used in practice is a conventional approach, in which settlements brought about by improved and unimproved layers are calculated separately, referred to as a two-layer system approach. By using the concept of the equivalent modulus of the composite mass, Rao and Ranjan (1985) proposed a simple method to predict the settlement of soft clay reinforced with floating stone columns under footing or raft foundations. The Japan Institute of Construction Engineering (JICE) (1999) proposed a method to calculate the settlement of soft soil treated by floating cement columns. When area replacement ratio $\alpha < 0.3(\alpha = A_c/A$; A_c = area of column and A = total influence area), the main contribution to the overall settlement will be the unimproved layer plus 1/3 of the improved layer. When $\alpha \geq 0.3$, JICE considers only the settlement contribution from the unimproved layer. Both methods are similar to equivalent raft methods used in pile group settlement calculations. A more recent study by Chai et al. (2009) proposed a method called the α–β method to determine the thickness of the part of the improved layer to be regarded as unimproved layer H_c. The method was developed based on the unit cell

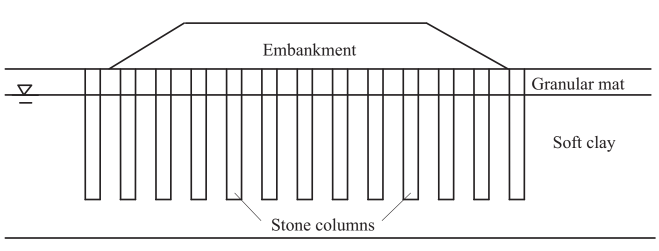

Fig. 1. Floating stone columns supporting an embankment.

concept simulated by the finite element method. From the results of numerical studies, the following functions were introduced:

$$H_c = H_L f(\alpha) g(\beta)$$
$$f(\alpha) = \begin{cases} 0.533 - 0.013\alpha & (10\% \leq \alpha \leq 40\%) \\ 0 & (\alpha > 40\%) \end{cases}$$
$$g(\beta) = \begin{cases} 1.62 - 0.016\beta & (20\% \leq \beta \leq 70\%) \\ 0.5 & (70 \leq \beta \leq 90\%) \end{cases} \quad (1)$$

where H_L = treatment depth, α = area replacement ratio, and β = ratio of column length over soft soil thickness. This method is only suitable for load intensities of 50–160 kPa for cement columns.

To the authors' knowledge, no method is currently available in the literature that can predict the degree of consolidation of floating stone columns. However, an analytical solution for the consolidation of double soil layers has been proposed by Zhu and Yin (1999). Their solution takes into account the influence of the permeability, the compressibility, and the thickness of each layer. Due to the complexity of the solution, however, its application is not widely accepted by practicing engineers.

This paper aims to investigate the performance of floating stone columns under uniform wide spread loading, with 2D unit cell axis-symmetry idealization. The unit cell model comprises a single stone column and its equivalent circular influence zone. It is used to represent a column located on the interior of an infinitely large group of stone columns (Balaam and Booker, 1985). The idealization is made to simulate the case of a rigid raft or large uniform loaded area as in the case of an embankment. Since load and geometry are symmetrical in the unit cell, the boundary conditions of the outer wall are zero shear stress, zero radial displacement, and no water flow (Castro and Sagaseta, 2009). However, it does not strictly conform to