Soils and Foundations 2015;55(1):154–165

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Soils and Foundations

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Simplified homogenization method in stone column designs

K.S. Ng[a,*], S.A. Tan[b,1]

[a]Faculty of Civil Engineering, University Teknologi MARA, 40450 Shah Alam, Malaysia
[b]Department of Civil and Environmental Engineering, University of Singapore, Singapore 119260, Singapore

Received 28 December 2013; received in revised form 29 September 2014; accepted 21 October 2014
Available online 2 January 2015

Abstract

The homogenization technique has been developed to model stone column improved grounds by establishing the equivalent material properties for the composite ground. However, homogenization techniques based on the elasto-plastic behavior of the constituent materials found in literature require modification in terms of the finite element constitutive models which are difficult for practical engineers to apply. Therefore, a simple yet effective way of predicting the consolidation performance of stone column improved grounds has been invoked in this study. The method is called the equivalent column method (ECM). The new method provides not only equivalent stiffness for the composite material, but also equivalent permeability. The method is derived from an analysis using the unit cell model in a 2D finite element axisymmetrical model. The settlement is calculated and a correction factor is obtained via a comparison with the results calculated using a single averaging composite stiffness for the improved ground. Correlations are summarized in the form of design charts for the key parameters, such as the area replacement ratio, the loading intensity, and the friction angle of the column material. Through a series of tests for different area replacement ratios, the equivalent permeability is established and presented in a design chart for different permeability ratios. ECM shows a good agreement with the current design methods and field results. The advantage of the proposed method over other homogenization techniques is the simplicity of its use which renders easy model set-up in the finite element program, especially for embankments and large tank problems, besides its extra ability to predict the consolidation time.
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Keywords: Stone column; Equivalent stiffness; Equivalent permeability; Homogenization method; Finite element; Consolidation

1. Introduction

Stone column improved grounds are composite grounds made up of granular material and soft soil. The behavior of these composite grounds is not well understood because of their non-homogenous structural matrix. A lot of research has been carried out to study the performance of composite grounds (Maheshwari and Khatri, 2012; Babu et al., 2013; Ng and Tan, 2014a; Killeen and McCabe, 2014) and many of them have adopted the unit cell concept in their analysis. The unit cell concept is a clever simplification for composite grounds used to model infinite column grid conditions, but the assumptions may break down in some situations. For instance, Schweiger and Pande (1986) noted that assumptions made in the unit cell concept are valid only for rigid rafts and that the assumptions have severe weaknesses in regard to the boundary conditions. On the other hand, the homogenization methods were invoked in an era when computational capacity was limited in terms of modeling complicated numerical models (Lee and Pande, 1998; Wang et al., 2002; Vogler

*Corresponding author. Tel.: +60 127537936.
E-mail addresses: ngkokshien@ppinang.uitm.edu.my (K.S. Ng), ceetansa@nus.edu.sg (S.A. Tan).
[1]Tel.: +65 65162278.
Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2014.12.012
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Nomenclature

b_c	plain strain column width
b_s	homogenized stress ratio
b_t	stress distribution tensor
c_v	coefficient of consolidation in vertical direction
d	soft soil thickness
d_c	diameter of column
d_e	equivalent influence of diameter
d_s	diameter of smear zone
f_s	volume fraction of inclusion in matrix
f_y	correction factor
k	coefficient of permeability
m	modular ratio
m_v	coefficient of volume compressibility
n	settlement improvement factor
n_s	stress concentration ratio
q_{uh}	homogenized strength
q_{ult}	ultimate bearing capacity
q'_u	macro stress failure
r_c	radius of column
r_e	radius of influence area
s	spacing of columns
t	time
A	total influence area
A_c	area of stone column
A_s	area of soil
B_p	equivalent plain strain width
D_c	constraint modulus of column
D_s	constraint modulus of soil
D_{comp}	constraint modulus of composite soil
E	Young's modulus
E_c	Young's modulus of column
E_s	Young's modulus of soil
E_q	equivalent stiffness
E_{comp}	composite stiffness
E_{50}	secant modulus
K_o	initial horizontal to vertical stress
k	coefficient of permeability
$k_{composite}$	composite permeability
k_{eq}	equivalent permeability
L	length of stone column
N_{corr}	correction factor
N	diameter ratio
S	diameter ratio of smeared zone to drain well
T_v	time factor in vertical flow
T'_v	modified time factor in vertical flow
U	degree of consolidation
U_v	degree of consolidation for vertical flow
δ	settlement
α	area replacement ratio
β	depth ratio

and Karstunen, 2008). The homogenization method assumes that the columns are distributed homogenously within the in situ soil. It allows for adopting non-linear constitutive models for both the columns and the soil. The equilibrium and the compatibility conditions have to be satisfied through a stress–strain redistribution. The theoretical development of a new stress–strain behavior for composite grounds is complex and tedious.

Despite being an intuitive idea for solving the complex 3D problems of stone column improved grounds, the practical implementation of the homogenized constitutive law in the finite element code for composite grounds is still hardly compatible among design engineers albeit the finite element model set-up is simple, since the soil and the columns do not need to be discretized separately. Therefore, a simple homogenization method is developed in this study to obtain the equivalent stiffness and the equivalent permeability for the composite material that can be easily applied in a numerical model, while still considering the yielding characteristic of the composite material. This method is called the equivalent column method (ECM).

2. Review of related works

A few researchers have proposed some simple formulations for the equivalent stiffness of the composite soil. Their methods are discussed briefly in this section.

Poorooshasb and Meyerhof (1997) examined the efficiency of end-bearing columns by developing an analytical model with assumptions of geometric linearity and the use of the small strain theory. The following governing equation is used for columns with linear elastic material:

$$\frac{UDL}{\delta/L} = A\{1+Bv_c\}\frac{r_e^2-r_c^2}{r_e^2} + \left\{E_c+2v_c[AC(1+Bv_c)+Dv_c]\right\}\frac{r_c^2}{r_e^2} \quad (1)$$

where UDL=uniform distributed load carried by the stone column system; δ=settlement of the foundation system; L=length of the column; E_c=Young's modulus of the column material; ν_c=Poisson's ratio of the column material; E_s=Young's modulus of the in situ soil; ν=Poisson's ratio of the in situ soil; r_c=radius of the column; r_e=radius of the influence zone; and constants A, B, C, and D are given by

$$A = \frac{(1-v)}{1-2v^2-v}E_s$$
$$B = \frac{2v}{1-v}\frac{r_c^2}{r_e^2-r_c{}^2}$$
$$C = \frac{v}{1-v}$$
$$D = \frac{(1+v)r_c^2+(1-v)r_e^2}{(1-v^2)(r_e^2-rc^2)}E_s$$

Omine et al. (1998) proposed a homogenization method to evaluate the stress–strain relationship of the two-phase mixture

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