Computers and Geotechnics 92 (2017) 96–107

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

# A simplified axisymmetric model for column supported embankment systems

Lin-Shuang Zhao [a], Wan-Huan Zhou [a,b,*], Ka-Veng Yuen [a]

[a] Department of Civil and Environmental Engineering, Faculty of Science and Technology, University of Macau, Macau
[b] UMacau Research Institute, Zhuhai, Guangdong, China

ARTICLE INFO

*Article history:*
Received 25 April 2017
Received in revised form 16 July 2017
Accepted 31 July 2017

*Keywords:*
Column supported embankment
Axisymmetric model
Load transfer
Modulus ratio
Stress ratio

ABSTRACT

In this study, a simplified axisymmetric model is built to simulate a column supported embankment system. The model is based on a cylindrical unit cell that contains one column with the surrounding soil and a layer of overlying embankment fill. The deformation of the column with the surrounding soil is simulated using a deformed shape function. The embankment fill is divided into an inner cylinder and an outer hollow cylinder to simulate the soil arching effect. The stress continuity and volume deformation continuity are applied to combine the behavior of the embankment fill and that of the column-reinforced foundation together. A semi-analytical solution is obtained, and it is verified using a finite element analysis and a case study. After that, parametric studies are put forward to evaluate the load transfer mechanism within the embankment fill, the shear stress at the interface between the column and the surrounding soil, and the vertical stress distribution within the column. The influences of the column modulus, the spacing between columns, the height of the embankment fill, and the length of the column on the soil arching effect are investigated and discussed. It is concluded that when the column modulus becomes larger, the stress ratio between the column and the surrounding soil increases correspondingly. The height of equal settlement plane is close to the net spacing between columns, but it changes slightly with a change in the column modulus.

© 2017 Elsevier Ltd. All rights reserved.

## 1. Introduction

Column reinforcement under an embankment system is a type of technique to strengthen the foundation soil and has been proven efficient in enhancing the bearing capacity [1–10], reducing the settlement of the embankment [11–19] and increasing the consolidation rate [20–22]. Some researchers adopted geosynthetic reinforcements [23–31] to make the load transfer more efficient within the embankment fill. Because of the imbedded columns, the stiffness of the foundation is no longer uniform. As the modulus of the column is much larger than that of the surrounding soil, it will result in a larger settlement in the foundation soil [32,33] in contrast to that of the column under the uniform load of the embankment fill. This differential settlement in the column-reinforced foundation that causes part of the embankment fill above the foundation soil has a tendency to move downward. This movement triggers shear resistance within the embankment fill, which transfers the load of the embankment fill endured by the surrounding foundation soil onto the column. Consequently, the stress increases on the column but decreases on the surrounding foundation soil. This is the soil arching effect. Hewlett and Randolph [34] used an arch to describe the soil arching effect in a two-dimensional model and used a dome in a three-dimensional model. Based on Hewlett and Randolph's theory [34], Low et al. [35] included cap beams and a layer of geotextile to investigate the influences on the load transfer efficiency. Kempfert et al. [36] proposed the multi shell arching theory, and it was adopted in EBGEO [37] and recommended in BS8006 [38] as an alternative design method. Van Eekelen et al. [39] proposed a novel analytical model using concentric arches based on the limit-state equilibrium theory to describe the arching effect. Zhou et al. [6] investigated the group effect of soil arching using the finite element method. It can be found that these studies mainly concentrated on the soil arching effect and neglected the deformation of the columns. These theories are suitable for rigid piles made of concrete. However, with regard to some types of columns with a relatively small stiffness, such as stone columns and soil-cement mixed columns, the deformation cannot be negligible. The differential settlement between columns and the surrounding

---

* Corresponding author at: Department of Civil and Environmental Engineering, Faculty of Science and Technology, University of Macau, Avenida da Universidade, Taipa, Macau.

*E-mail addresses:* z.l.s0319@gmail.com (L.-S. Zhao), hannahzhou@umac.mo (W.-H. Zhou), kvyuen@umac.mo (K.-V. Yuen).

http://dx.doi.org/10.1016/j.compgeo.2017.07.027
0266-352X/© 2017 Elsevier Ltd. All rights reserved.

soil varies when using different types of columns. Consequently, it influences the soil arching effect. Han and Gabr [11] developed a numerical model to study the influence of the column stiffness on the differential settlement at the level of the pile top. Zheng et al. [40] investigated the influence of the column modulus on the consolidation process using ABAQUS. However, few researchers have introduced analytical models to study the influence of the column modulus on the soil arching effect. Alamgir et al. [41] studied the column-reinforced foundation without an overlying embankment fill and proposed a methodology to describe its deformation behavior. Different types of column moduli were considered to investigate the stress distribution within the column and the settlement at the ground surface. Based on this method, Deb and Mohapatra [42] analyzed the column supported embankment under two dimensional plane strain assumption. The methodology proposed by Low et al. [35] was incorporated in their research to study the soil arching effect. However, as Low et al.'s arching theory is based on an assumed arch, which has no relation to the differential settlement of the column-reinforced foundation, it cannot consider the influence of the modulus ratio between the column and the surrounding soil. However, given the importance of modulus ratio, Deb and Mohapatra [42] introduced a multiplying factor to take it into account.

In this study, a simplified mathematical model is proposed to study the load transfer mechanism within a column supported embankment. The influence of modulus ratio between the column and the surrounding soil is included. A semi-analytical solution is obtained based on the proposed model. The deformations of the column, the surrounding soil, and the overlying embankment fill are compatible by applying the stress continuity and volume deformation continuity at the bottom of the embankment fill. Parametric studies are carried out to study the behavior of the column supported embankment system. Some influencing factors are considered, such as the modulus ratio, the column spacing, the embankment height, and the length of the column. The stress ratio between the column and the surrounding soil is investigated and discussed based on these influencing factors. It is made an attempt to find the relationship between the height of equal settlement plane and the net spacing between columns. Finally, the shear stress at the interface between the column and the surrounding soil and the vertical stress in the column are discussed.

## 2. Mathematical model

Column supported embankments can be used with or without geosynthetic reinforcements. For a column-supported embankment system without geosynthetic layers, the diameter of column is commonly relatively large with a close column spacing. Some researchers found that the geosynthetic layer has little effect on the load transfer and the maximum settlement of the embankment when the tensile stiffness of the geosynthetics is less than 860 kN/m [11,43] or the column spacing is relatively close [27]. In this study, the column supported embankment system without geosynthetic reinforcements is studied and the effect of geosynthetic reinforcement is not considered. A general case of column supported embankment is shown in Fig. 1a. A soft foundation reinforced by a group of columns rests on an undeformable bedrock with an overlying embankment fill. The columns are arranged in a square pattern, as shown in Fig. 1b. The spacing and net spacing between the columns are denoted as $s$ and $s_n$, respectively. As presented in Fig. 2a, a cylindrical unit cell, which contains one column with the surrounding soil and an overlying embankment fill, is taken into account to study the load transfer mechanism. Under the axisymmetric assumption, one plane (Fig. 2b) is drawn from the cylinder to simulate the interactions between the column, the surrounding soil, and the embankment fill. The equivalent diameter of the unit cell, $d_e$, is determined based on the principle of area equivalence. The relationship between $d_e$ and $s$ can be expressed as:

$$\frac{\pi}{4}d_e^2 = s^2 \tag{1}$$

In the cylindrical unit cell, the methodology presented by Alamgir et al. [41] is adopted to simulate the behavior of the column-reinforced foundation. The embankment fill is assumed to be separated into two parts. One part is an inner cylinder with diameter $d_c$ resting on the top of the column; the other part is an outer hollow cylinder with outer diameter $d_e$ supported by the foundation soil around the column. This assumption was adopted by Chen et al. [13] as well. Because of the load from the embankment fill, as shown in Fig. 2, the deformation of the column-reinforced foundation will occur. Differential settlement between the column and the surrounding soil will develop. The outer hollow cylinder will move downward to fill the space developed from the compression of the foundation soil. Simultaneously, the relative movement between the inner cylinder and the outer hollow cylinder will occur, and the load of the outer hollow cylinder will arch to the inner cylinder through the friction at the interface between them. With the increase in the embankment height, the relative movement reduces gradually. Correspondingly, the differential settlement will decrease and finally reach a zero differential settlement plane, named the "plane of equal settlement" [44]. This is the behavior of a column supported embankment system based on the cylindrical unit cell assumption. This idealization simplifies the load transfer mechanism in the embankment. As the load distribution in the embankment is developed by the arching effect owing to the differential settlement between the column and the surrounding soil. The shape of the mobilized stress arching is dependent on many factors, such as the column spacing, the size and 3D patterns of columns, the arrangement of columns, and the properties of the embankment fill and foundation soil. In this simple idealization, using the inner cylinder and outer hollow cylinder, some factors are taken into account, such as the spacing and size of columns, the moduli of the embankment fill, the column, and the foundation soil. However, some factors are not considered, such as the 3D patterns of columns, the arrangement of columns, and other properties of the embankment fill and foundation soil. To simplify the analysis, the vertical stresses and vertical deformations at any cross-section of the inner cylinder are assumed to be uniform. It is equally applicable for that of the outer hollow cylinder and the column. Another limitation is that the realistic sliding surface may not exactly be at the assumed interface between the inner and the outer hollow cylinders.

### 2.1. Load transfer within the embankment fill

The friction between the inner cylinder and the outer hollow cylinder can be expressed as the following equation under the $K_0$ assumption:

$$f = \sigma K_0 \tan\varphi \tag{2}$$

where $\sigma$ is the vertical stress in the embankment fill. $K_0 = 1 - \sin\varphi$, and $\varphi$ is the friction angle of the embankment fill.

It is assumed that the datum point is at the level of the column top and downward is positive. As shown in Fig. 2d, dividing the inner cylinder into small pieces with the thickness of $dz$, and taking one unit element to study the friction between the inner cylinder and the outer hollow cylinder based on the force equilibrium in the vertical direction. It can be expressed as:

$$A_i d\sigma_i(z) = (\gamma A_i + \pi d_c f)dz \tag{3}$$

Download English Version:

https://daneshyari.com/en/article/4917974

Download Persian Version:

https://daneshyari.com/article/4917974

Daneshyari.com