Engineering Geology 168 (2014) 104–113

Contents lists available at ScienceDirect

Engineering Geology

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

Numerical investigation on factors for deep-seated slope stability of stone column-supported embankments over soft clay

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ARTICLE INFO

Article history:
Received 21 June 2013
Received in revised form 2 November 2013
Accepted 8 November 2013
Available online 16 November 2013

Keywords:
Factor of safety
Embankment
Slope stability
Stone column
Soft clay

ABSTRACT

Stone columns have been commonly used as an alternative to solve deep-seated slope stability problems. Due to the complexity of a three-dimensional (3-D) arrangement of multiple columns, a 3-D problem has been commonly converted into a two-dimensional (2-D) model which has equivalent properties and dimensions, by the column-wall method and the equivalent area method. In this paper, two column-wall approaches based on matching either column geometry or column properties were compared and verified by 3-D numerical results in the stability evaluation of the stone column-supported embankment over soft soils. This study also investigated the 2-D numerical models using the column-wall method and the equivalent area method considering the factors of stress concentration, area replacement ratio, and soil conditions under short-term and long-term conditions. The numerical results show that the equivalent area method resulted in a continuous critical slip surface in the stone column-supported embankment over soft soil; however, no continuous slip surface developed using the column-wall method. Under the short-term condition, the computed factor of safety by the equivalent area model with or without considering the stress concentration effect was greater than that computed by the column-wall model. However, their difference became smaller under the long-term condition. The columns at certain locations along a prescribed slip surface from the equivalent area method did not mobilize their shear strengths under the short term condition. A reduction factor of 0.9 is suggested to correct the calculated factor of safety by the equivalent area method without considering the stress concentration ratio to that by the column-wall method under the short-term condition. No reduction factor (or the reduction factor of 1.0) is proposed under the long-term condition.

1. Introduction

Deep-seated slope instability (also referred to as global slope failure) of embankments constructed on soft soils is one of the challenging problems to geotechnical engineers. A number of techniques have been successfully adopted to prevent deep-seated slope failure, such as sand compaction columns, stone columns, and deep mixed columns. As one of the ground improvement techniques, stone columns have been commonly used as an alternative to solve the deep-seated slope stability problem of embankments over soft soils.

Stone columns are commonly installed by a water jetting or air jetting cylindrical vibrating probe or a casing into the ground to form holes, which are backfilled with gravel or crushed rock densified by the vibratory probe or casing as it is withdrawn from the ground. Stone columns have the functions of increasing bearing capacity and slope stability, accelerating rate of consolidation, and reducing settlement (Han and Ye, 2001; McKelvey et al., 2004; Ambily and Gandhi, 2007; Han, 2012).

The instability of an embankment may result from local failure, surficial failure, toe slope failure, or deep-seated slope failure, which depends on the soil conditions, the strength of embankment fill, the height and slope angle of the embankment (Han et al., 2005). The failure modes of column-supported embankments over soft soils are more complicated due to the existence of the columns. The columns under the embankment load can fail due to bending, sliding, rotation, shearing, tension, or a combination of the failure modes (Kivelo and Broms, 1999; Han et al., 2005; Kitazume and Maruyama, 2006; Han, 2012). High shear forces and bending moments can be transferred to stiffer columns, causing the columns to fail in bending (Kivelo and Broms, 1999). Han et al. (2005) found the rotational failure of deep mixed columns subjected to an embankment load based on the numerical analysis. Kitazume and Maruyama (2006) observed the rotational failure mode of deep mixed columns under embankment loads in centrifuge tests and proposed a simple method to estimate the embankment pressure at failure based on the rotational failure mode. They also indicated that the area replacement ratio of deep mixed columns had a significant effect on the bending failure and the sliding failure might happen to the columns

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http://dx.doi.org/10.1016/j.enggeo.2013.11.004

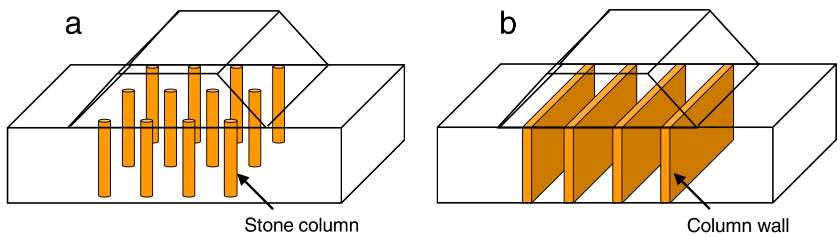

Fig. 1. View of stone column-supported embankment on soft soil: (a) individual columns; (b) column-walls.

with a relatively short length or in soil with its shear strength decreasing with depth. Shear failure has been commonly assumed for flexible columns, such as stone columns and sand compaction columns (Priebe, 1978; Abusharar and Han, 2011).

For slope stability analysis, Bishop's simplified method (Bishop, 1955) assuming a circular slip surface is probably the most commonly-used limit equilibrium method. However, Han et al. (2004) indicated that the critical slip surface of the deep-seated slope failure of a deep mixed column-support embankment over soft soil was not circular based on the numerical results. As compared with the limit equilibrium method, the numerical method has its advantages on stability analysis (for example, no pre-defined slip surface is needed; and equilibrium, stresses, and yield conditions are satisfied everywhere.). Han et al. (2004) showed that the limit equilibrium analysis using Bishop's simplified method (Bishop, 1955) overestimated the factor of safety of the embankment over a deep mixed column-reinforced foundation as compared with the numerical method. Abusharar and Han (2011) numerically investigated the influence of the column spacing, the properties of column, clay and embankment fill, and the ground water on the stability of stone column-supported embankments over soft soils. Zheng et al. (2010) numerically found that the embankments over rigid column-reinforced foundations might fail due to bending and rotation.

In the column studies, due to the complexity of a three-dimensional (3-D) multi-column problem, various methods have been proposed to convert the 3-D problem into a two-dimensional (2-D) model which has equivalent properties and dimensions. All the plane strain equivalency methods can be classified into the two basic types, i.e., the column-wall method and the equivalent area method (Christoulas et al., 1997; Cooper and Rose, 1999; Tan et al., 2008; Abusharar and Han, 2011). From the elasto-plastic numerical analysis on the stone column-supported embankment over soft soils, Tan et al. (2008) indicated that the computed long-term settlements by the column-wall model based on the equivalent column properties were more accurate than those by the column-wall method based on the equivalent column geometry. However, the applicability and validity of these two column-wall methods to evaluate the slope stability of stone column-supported embankments have not been explored so far. Abusharar and Han (2011) recommended a reduction factor of 0.9 for the factor of safety calculated by the equivalent area model to that by the column-wall model under the short-term condition. This finding is useful in predicting the factor of safety of the multi-column-supported embankment over soft soil. However, the reason for such a reduction in the factor of safety has not been well examined. Moreover, the possible difference between the equivalent area method and the column-wall method under long-term condition has not been investigated.

This paper presents numerical analyses to investigate the factor of safety of the embankment over stone column-improved soft soils under short-term and long-term conditions. Two column-wall methods proposed by Tan et al. (2008) in the evaluation of the stability of the stone column-supported embankment over soft soils were compared and verified by the 3-D numerical analysis. A numerical study was conducted to evaluate the column-wall method versus the equivalent area method considering the factors of stress concentration, area replacement ratio, and soil conditions under short-term and long-term conditions. To investigate the reasons for the difference in the computed factor of safety between the column-wall method and the equivalent area method, slip surfaces and the soil stress states on the slip surface were explored. Based on the numerical results, reduction factors were proposed to account for the difference in the factor of safety under the short-term and long-term conditions when the equivalent area model is used in practice.

2. Two-dimensional equivalency methods

As described previously, a 3-D problem of column-supported embankments can be converted to an equivalent plane strain problem using the column-wall method and the equivalent area method. This section below briefly describes these two equivalency methods.

2.1. Column-wall method

Individual stone columns in Fig. 1(a) can be converted to column-walls in Fig. 1(b) for a plane strain analysis. In this conversion, two approaches have been commonly used, by matching the geometry of the columns or the properties of the columns (Tan et al., 2008).

The method by matching the geometry of the columns is referred to as Method 1 in this paper. In this method, the effective width of the column-wall is assumed to be the same as the diameter of individual columns (i.e., $b_w = d_c$, in which, b_w is the width of the column-wall and d_c is the diameter of individual columns). The equivalent properties of the column-walls, such as equivalent elastic modulus, cohesion, and friction angle, are determined based on the area-weighted average of the properties of the stone columns and the surrounding soft soils within each row of columns:

$$E_w = E_c a_r + E_s(1-a_r) \tag{1a}$$

$$c_w = c_s(1-a_r) \tag{1b}$$

$$\phi_w = \arctan(a_r \tan\phi_c + (1-a_r)\tan\phi_s) \tag{1c}$$

where E_w, E_c, and E_s are the elastic moduli of column-walls, individual stone columns, and soft soils, respectively; c_w and c_s are the cohesion of column-walls and soft soils, respectively; ϕ_w, ϕ_c and ϕ_s are the friction angles of column-walls, individual stone columns, and soft

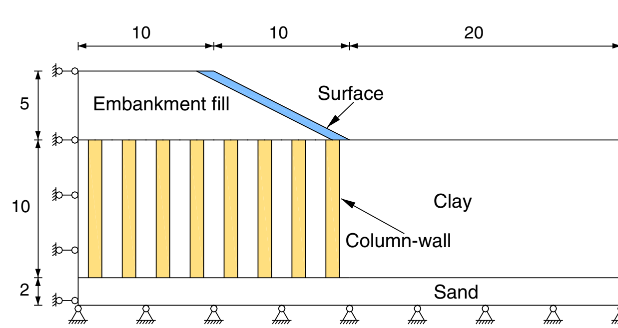

Fig. 2. Cross section of the embankment model based on the column-wall method (not to scale; unit: m).