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Two-dimensional deep-seated slope stability analysis of embankments over stone column-improved soft clay

Sari W. Abusharar, Jie Han *

Dept. of Civil, Environmental, and Architectural Engineering (CEAE), the University of Kansas, 1530 West 15th St., Lawrence, Kansas 66049–7609, USA

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ABSTRACT

A two-dimensional (2D) finite difference method was adopted in this study to estimate the factor of safety (FS) against deep-seated failure of embankments over stone column-improved soft clay based on individual column and equivalent area models. In the equivalent area model, the equivalent parameters (unit weight, cohesion, and friction angle) for the improved area were estimated based on the area average of the parameters from stone columns and soft clay. The factors influencing the FS against deep-seated failure of embankments over stone column-improved soft clay were investigated including the spacing, size, and friction angle of stone columns, cohesion of soft clay, friction angle and height of embankment fill, and existence of ground water. Based on the numerical results, a reduction factor was proposed to account for the difference in the FS when the individual column model is converted to the equivalent area model. The effects of the influence factors on the reduction factor were also investigated. The comparative study shows that the FS values obtained by the equivalent area model are higher than those by the individual column model. The results of these analyses are summarized into a series of design charts, which can be used in engineering practice. A reduction factor for FS of 0.90 is appropriate to convert the calculated FS by the equivalent area model to that by the individual column model based on the current study. Furthermore, the existence of the water table results in lower FS values than the cases without considering a water table because the groundwater reduces the shear strength of the improved foundation.

1. Introduction

Problems of slope instability present design and research challenges to geotechnical engineers. Slope stability analysis can be carried out by the limit equilibrium method (LEM), the limit analysis method (LAM), the finite element method (FEM), and the finite difference method (FDM) (Han and Leshchinsky, 2006; Cheng and Lau, 2008).

In recent years, finite difference method has been widely used for analyzing slope stability including the computation of its factor of safety (FS) (for example, Dawson et al., 1999; Cala and Flisiak, 2001; Han et al., 2002; Cala and Flisiak, 2003a,b; Shukha and Baker, 2003; Han and Leshchinsky, 2004; Han et al., 2004; Richards and Reddy, 2005; Apuani et al., 2005; Han et al., 2005; Won et al.;, 2005; Cheng et al., 2007; Han et al., 2008; Sun et al., 2008; Srivastava and Sivakumar Babu, 2009). Dawson et al. (1999) indicated that the FS values of unreinforced slopes obtained using the finite difference method in the FLAC software were in good agreement with those using the limit equilibrium method with a log-spiral slip surface. Han et al. (2002) used the same finite difference software (FLAC) to obtain the identical corresponding FS values of unreinforced and geosynthetic-reinforced slopes as the Bishop's simplified method. Han and Leshchinsky (2004) obtained similar results for mechanically stabilized earth (MSE) walls using the finite difference method and Bishop's simplified method incorporated in the ReSSA software.

The finite difference method is perhaps one of the oldest numerical techniques used for solving sets of differential equations. In the finite difference method, every derivative in the set of governing equations is replaced directly by an algebraic expression written in terms of the field variables at discrete points in space; these variables are undefined within elements (Itasca Consulting Group, Inc., 2006). As compared with limit equilibrium methods, finite difference methods have the following advantages for calculating the factor of safety of slope stability (Dawson and Roth, 1999; Cala and Flisiak, 2001): (1) no need to define a range of trial surfaces and possible failure modes or critical slip zones determined from the numerical results (e.g., strain rate, plasticity); (2) no need to assume any functions for inter-slice force; (3) different failure surfaces possibly occurring at the same time; (4) structural elements used to better simulate inclusions (e.g., rock bolt, soil nail or geogrid) instead of equivalent forces; and (5) the solution consisting of kinematically feasible mechanisms.

The slope instability of embankments may develop locally, near the facing, within the embankment, or through the foundation soil as local, surficial, general, or deep-seated failure, as shown in Fig. 1. The deep-seated slope failure is also referred to as a global slope failure,

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* Corresponding author. Tel.: +1 785 864 3714; fax: +1 864 5631.
E-mail addresses: engsariw@hotmail.com (S.W. Abusharar), jiehan@ku.edu (J. Han).

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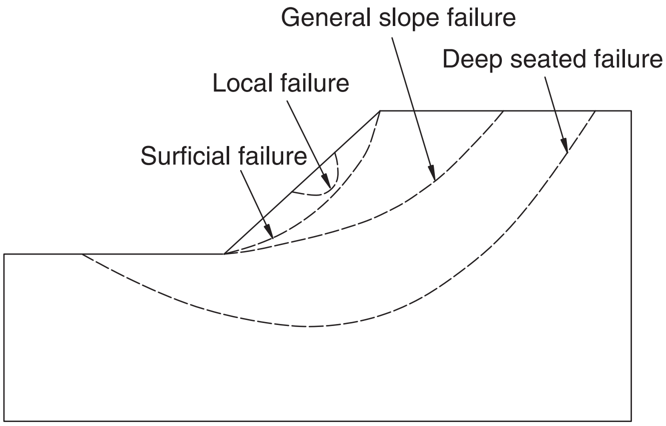

Fig. 1. Potential slope stability failures (Han et al., 2004).

mainly induced by a weak foundation existing under the embankment. Local and surficial failures develop at a shallow depth (mostly less than 1.2 m) due to low overburden stress, low density, low strength, and seepage force when the slope becomes saturated after rain. The general slope failure typically occurs through the toe of the slope (Han et al., 2004).

A number of ground improvement techniques have been successfully adopted to prevent deep-seated slope failure, such as sand compaction piles, stone columns, and deep mixed columns. Stone columns have been commonly used as an alternative to solve deep-seated slope stability problems (Hughes et al., 1975; McKenna et al., 1975; Rathgeb and Kutzner, 1975; Aboshi et al., 1979; Datye and Nagaraju, 1981; Bergado et al., 1988; Bergado et al., 1990; Christoulas et al., 1997; Cooper and Rose, 1999). The stone column technique was adopted in European countries in the early 1960s and thereafter it has been used successfully worldwide to increase bearing capacity, reduce settlement, and accelerate consolidation (Hughes et al., 1975; Priebe, 1995; Han and Ye, 2001). Stone columns can be installed using a wet or dry method. The wet method employs a vibrating probe with jetting water to form holes to be backfilled with stones from a ground surface while the dry method uses a vibrating probe with jetting air down to a depth and a feed pipe to supply stone to the bottom of the probe. The stone columns improve the ground mainly due to their higher strength and stiffness compared to the soil. Stone columns have higher strength and stiffness than sand compaction piles because of the quality difference between stone and sand. Different from deep mixed columns, the strength of stone columns depends on the friction angle of the stones and the confining stress in the field. The deep-seated slope stability of embankments over deep-mixed columns was investigated by Han et al. (2005). Ambily and Gandhi (2007) considered that the most critical factor which controls the design of the stone column-improved ground is the stiffness of the column and load sharing between column and soil. Christoulas et al. (1997) investigated the stability of embankments over stone columns using a limit equilibrium method with a slip circle, in which individual stone column and equivalent area models were analyzed. They concluded that the computed factor of safety from the individual column method was greater than that from the equivalent area method. Han et al. (2005, 2008) found that the slip surfaces for the improved foundation with individual deep mixed columns are not continuous and non-circular. Therefore, whether the limit equilibrium method with slip circles is suitable for analyzing the stability of embankments over individual stone columns is questionable.

This paper presents a series of two-dimensional (2D) finite difference analyses to investigate the factors influencing the FS against deep-seated failure of embankments over stone column-improved soft clay. The finite difference method incorporated in the software – FLAC/Slope Version 5.0 is designed specifically to perform factor of safety calculations for slope stability analysis. The parameters investigated are the spacing, size, and friction angle of stone columns, the cohesion of soft clay, and the friction angle and height of embankment fill. The effect of the water table on the stability of the slope was also evaluated. The results of these analyses are summarized into a series of design charts, which can be used in engineering practice. Based on the numerical results, a reduction factor was proposed to account for the difference in the FS when the individual column model is converted to the equivalent area model.

2. Two-dimensional finite difference analysis

2.1. Problem dimensions

Fig. 2 shows that the model considered here consists of an embankment supported by stone columns in soft clay under a two-dimensional (2D) plane strain condition. The foundation soil consists of 10 m thick clay overlying 2 m thick sand. Due to the symmetry of the model, half of the cross-section was analyzed using the software FLAC/Slope Version 5.0 developed by Itasca Consulting Group, Inc. The stone columns were modeled as continuous walls parallel to the centerline of the embankment as shown in Fig. 2a. The dimensions and spacing of stone columns and the overall embankment and foundation dimensions were selected based on a common practice in the field. Similar dimensions were used by Han et al. (2007) in another study. These parameters of the baseline case are provided as follows: width of columns = 0.8 m, length of columns = 10 m; crest width of embankment = 20 m (half width is shown in Fig. 2), height of embankment = 5 m, angle of side slope = 2 H:1 V. The clear spacing between adjacent columns was set at 3.2 m. The groundwater table was at the ground surface. An “Exclude” function included in the FLAC/Slope software was adopted to prevent the potential failure surface from entering a 0.5 m thick surficial soil layer on the slope. In other words, any failure above the foundation was prevented. The above values were used throughout this study unless otherwise specified.

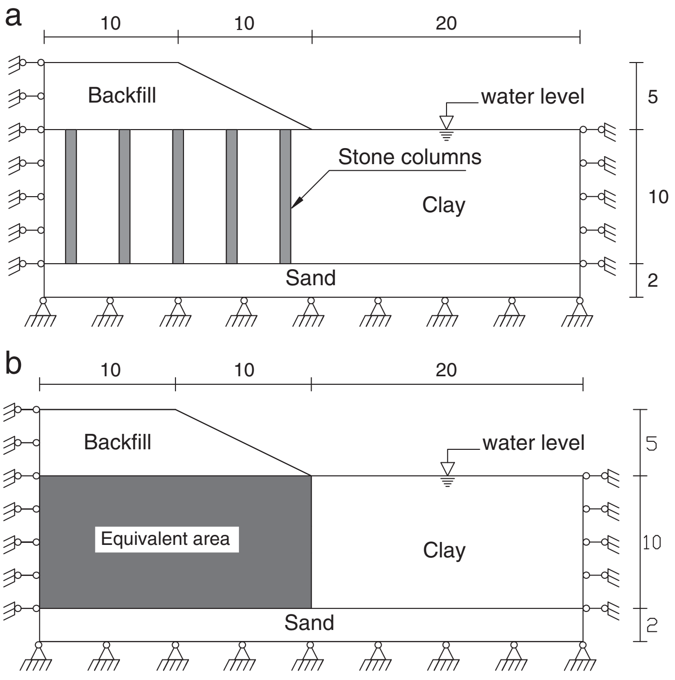

Fig. 2. Cross sections of calculation models for the finite difference analysis of (a) individual columns and (b) an equivalent area (all dimensions in meters).