Computers and Geotechnics 97 (2018) 124–133

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Technical Communication

Undrained stability of strip footing above voids in two-layered clays by finite element limit analysis

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ARTICLE INFO

Keywords:
Strip footing
Voids
Finite element limit analysis
Undrained bearing capacity
Clays

ABSTRACT

Finite element limit analysis (FELA) is used to study the undrained bearing capacity of strip footing above voids in two-layered clays. Based on the FELA results, design charts and equations are provided to calculate the undrained bearing capacity factor N_s. The impact of parameters on N_s also has been investigated, including undrained shear stress ratio of the soil, thickness of the top layer, location, size, width, height and spacing of the voids. The failure mechanisms for a single void maybe classified into three categories: roof failure, combined roof and wall failure, bearing failure without void failure.

1. Introduction

The presence of underground voids maybe due to two reasons: (1) human activities such as tunneling, mining and subway excavation; (2) dissolution of soluble material (eg. salt, dolomite and limestone). The formation of Karst cavities in a limestone stratum is a typical example of dissolution, which may exist at any depth. These voids could cause structure collapse, settlement of roads and loss of life, which need special attention in engineering practice.

Several studies have been conducted to evaluate the stability of strip footing above voids. Baus and Wang [1] investigated the bearing capacity of strip footing above continuous voids in silty clay by experimental investigation and numerical modeling, and concluded that the bearing capacity of strip footing depends greatly on the size and location of the void. Wang and co-workers continuously studied the effects of underground voids on strip footing stability using finite element method (FEM), and indicated that there is a critical region under the footing [2, 3]. Wood and Larnach [4] reported model tests of footings located above voids, together with FEM results. Wang and Hsieh [5] analyzed the collapse load of strip footing above circular void by using upper bound theorem of limit analysis, and three failure mechanisms are summarized. Considering the effect of footing sizes, void sizes and locations on the collapse load of strip footing, Wang et al. [6] extended the work conducted by Wang and Hsich [5], and revealed ten failure mechanisms. Al-Tabbaa et al. [7] reported the results of model tests of strip footing above continuous circular voids in gypsum-sandy soil mixture. The results revealed that the bearing capacity of footings increases with increasing the depth and offset of the void. Azam et al. [8] explored the bearing capacity of strip footing centered above a single circular void in two-layered clays by using FEM, and design equations are provided. More recently, Kiyosumi et al. [9] employed finite element code Plaxis 1998 to investigate the bearing capacity of strip footing above multiple voids. They summarized a tendency for a failure zone to develop near the nearest void. Kiyosumi et al. [10] performed a series of 1G loading tests of strip footings on stiff ground with continuous square voids, and three upper-bound mechanisms for a single void are observed, namely, roof failure, sidewall failure, and combined failure. The behavior of surface footing on reinforced sand beds with voids also has been explored [11–13]. Under undrained conditions, Lee et al. [14] adopted finite element code Plaxis 2012 to study the undrained stability of a strip footing on homogeneous and non-homogeneous clay with continuous voids, and the influence of load inclination was also examined [15]. The results are presented as failure envelopes for use by engineers. Lavasan and Ghazavi [16] investigated the behavior of strip footing on twin voids using a 2D plane-strain FEM analysis, and concluded that the failure mechanisms are dependent on the size and location of the voids as well as the footing. As reviewed above, no publication concerns on the undrained stability of strip footing above voids in two-layered clays.

The methods of FELA adopt a discrete form of the bound theorems of classical plasticity to formulate an optimization problem that is solved using quasi-Newton nonlinear programming or second order conic programming [17]. These techniques do not require assuming a probable collapse mechanism and the load-settlement curve to define the bearing capacity of strip footing above voids, which are developed by Lyamin and Sloan [18, 19] and Krabbenhøft et al. [20, 21]. There are two distinct solutions produced: (1) the upper bound (UB) solution, which is based on kinematically admissible velocity fields; (2) the lower

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https://doi.org/10.1016/j.compgeo.2018.01.005
Received 29 October 2017; Received in revised form 5 January 2018; Accepted 10 January 2018
0266-352X/

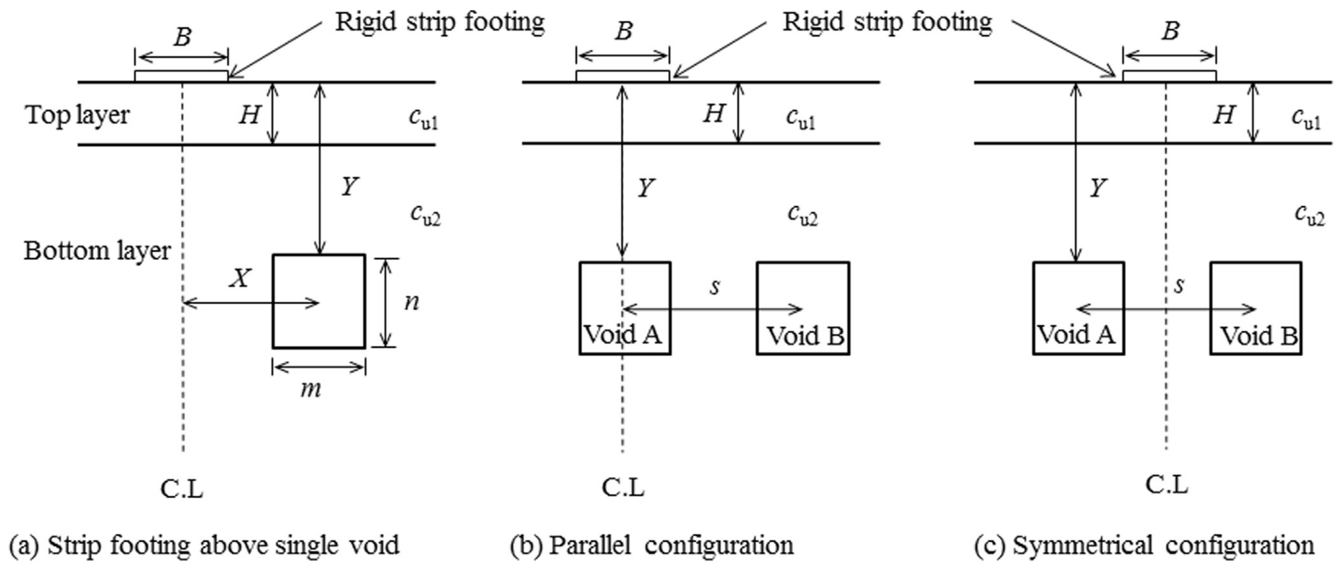

Fig. 1. Problem definition.

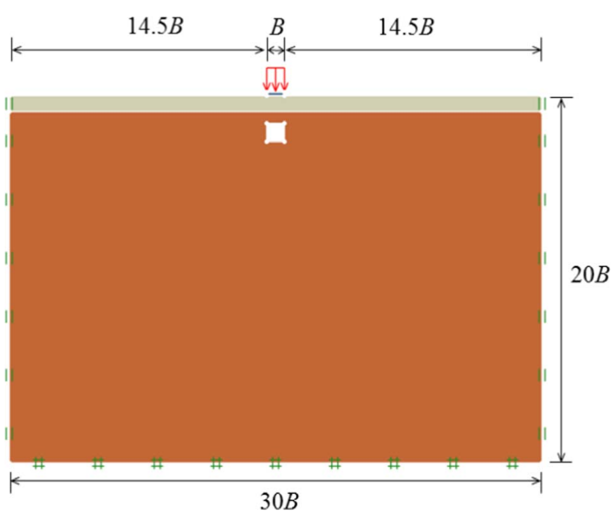

Fig. 2. Numerical model of strip footing in two-layered clays with single void in OptumG2.

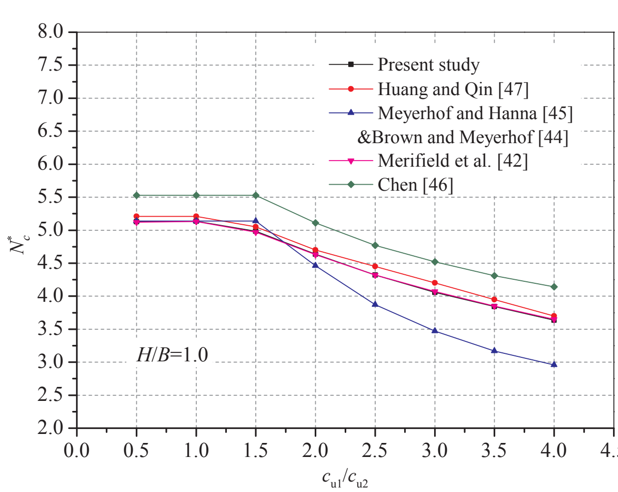

Fig. 3. Comparison of undrained bearing capacity factor N_c^* for strip footing in two-layered clays without voids.

bound (LB) solution, which is based on statically admissible stress fields [22]. Accurate computation of the UB and LB bounds could determine the true collapse load with a high degree of confidence [23]. In addition, the methods of FELA obtaining the limit load directly are often employed to analyse the geotechnical stability problems, without the need to perform a complete incremental analysis [24]. Because of the efficiency of FELA, it has been widely used in bearing capacity calculation of strip footings [25–28], stability analysis of tunnels [29–33], slopes [34–36] and anchors [37–40].

This paper investigates the undrained stability of strip footing above voids in two-layered clays, by using OptumG2 [41], a recently developed software based on FELA. In order to evaluate the bearing capacity of strip footing above voids in two-layers under undrained condition, a bearing capacity factor is defined, relative the undrained shear strength ratio of the two clays, thickness of the top layer, location, shapes and quantities of the voids. Based on the analyses, the results presented in design charts, and the collapse mechanisms are discussed.

2. Problem definition

Fig. 1 shows the problem considered and defines the main geometrical parameters. A strip footing of width B is placed on a top layer of clay with thickness H and undrained shear stress c_{u1}. A top layer is underlain by a clay layer that has infinite depth and undrained shear stress c_{u2}. As illustrated in Fig. 1(a), symbols m and n, respectively, indicate the void's width and height. The horizontal distance from the center of the single void to the centreline of the footing is given by X; the vertical distance from the top of the single void to the ground surface is given by Y. Fig. 1(b) and (c) show two voids parallel and symmetrical configurations, respectively. Assume that void A and B have the same shape, size at the same depth. The horizontal distance between these two void centers is defined as s.

Merifield et al. [42] adopted a modified bearing capacity factor to calculate the ultimate bearing capacity of two-layered clays without voids, which can be expressed in the form

$$N_c^* = \frac{q_u}{c_{u1}} \tag{1}$$

where N_c^* is the modified bearing capacity factor, q_u is the ultimate bearing capacity, and c_{u1} is the undrained shear stress of the top layer.

Similarly, the bearing capacity problem investigated in this study is also evaluated by N_s, which is defined as