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Undrained stability of surface strip footings above voids

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ABSTRACT

This paper investigates the undrained vertical bearing capacity of surface strip footings on clay with single and dual continuous voids. Numerical solutions for a wide range of geometric and material combinations are obtained by small strain finite element analysis. Based on the results, design charts are provided for the calculation of the undrained bearing capacity factors as a function of the dimensionless parameters related to the vertical and horizontal void distances from the footing, void width and height, and spacing between the two voids as well as soil rigidity and non-homogeneity. In the footing-above-void system, the ultimate bearing capacity of the footing is governed by the three failure mode: roof, wall, and combined failure mechanisms.

1. Introduction

In engineering practice, the existence of underground voids under rigid surface structures (e.g., pavements, pipelines and footings) requires special attention because voids can influence the integrity of structures. Voids in ground are known to form for many reasons, some of which are the thawing of subsurface ice lenses [1], the dynamic loadings induced by mining and tunneling activities [2], the dissolution of soluble materials such as salt, gypsum, limestone and dolomite [3], the dissociation of methane hydrate [4], and the presence of leaking CO_2 storage reservoirs [5]. The size, shape and evolution of voids depend on the lithology of soils and rocks, and the initial depth of voids [6]. In particular, large voids are often found in karstic environment [7].

The performance of footings underlain by subsurface voids has been investigated by several researchers. Baus and Wang [8] studied experimentally and numerically the bearing capacity behavior of strip footings on silty clay with single continuous voids, and showed that for a given void size, the bearing capacity decreases as the distance between the footing and void reduces. Wang and his colleagues continuously explored the effects of void location, size, shape, and orientation with respect to the footing axis on the stability of square footings with different sizes, shapes and embedment depths [9,10]. Wood and Larnach [11] conducted another study on this subject by using physical modeling and numerical simulation, and reported similar behaviors observed in Wang's works. Wang and Hsieh [12] developed the three failure mechanisms that are considered to model the collapse of strip footing centered above a single circular void by using the upper bound theorem of limit analysis. Al-Tabbaa et al. [13] observed the load-settlement characteristics of model strip footings over continuous circular voids in cemented mixed sand. The results indicated that the greater depth and offset of voids cause the higher strength and stiffness of the system. Sreng et al. [14] presented the result of rotation response of strip footings above continuous square voids, which is obtained by measuring both vertical and horizontal displacements during 1 g model tests. More recently, Kiyosumi et al. [15] performed plain strain finite element (FE) analyses to examine the influence of multiple voids on the yield pressure of strip footing resting on calcareous soil, and stated that the failure zone developed significantly towards the nearest void from the footing and does not typically extend to the other voids. Kiyosumi et al. [16] reported the results of laboratory scale model tests of strip footing on stiff ground with continuous square voids and revealed the three types of collapse modes for a single void: bearing failure without void collapse, bearing failure with void collapse, and void failure without bearing failure. Even though several studies have been reported on the footing-above-void system, most works have focused on cohesive-frictional soils. In contrast, the undrained stability of footings overlying voids has not been discussed in the literature.

The bearing capacity of surface strip footings (both drained and undrained) is usually estimated using the bearing capacity formula suggested by Meyerhof [17]. The solution for the simplest case of undrained condition is identical to the exact solution of Prandtl [18], which is expressed as

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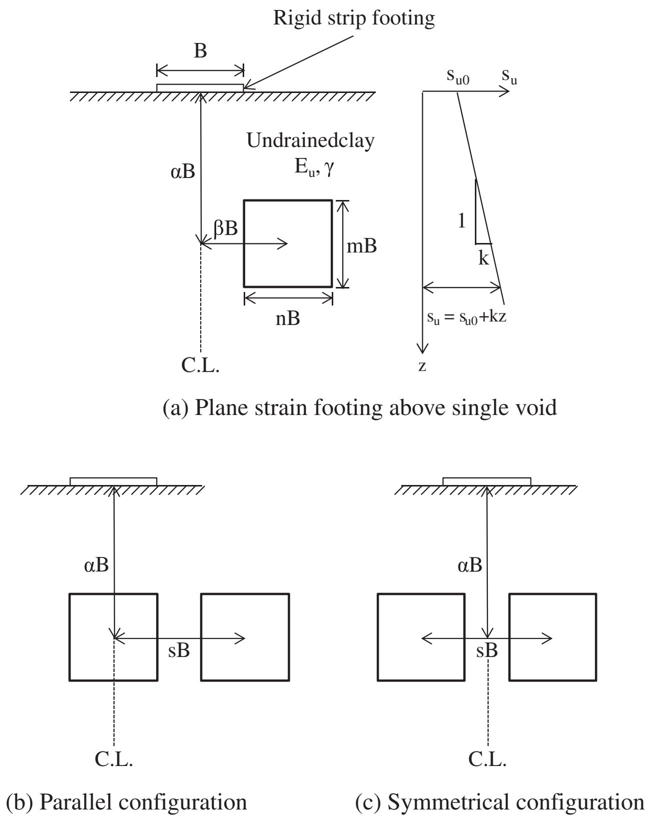

Fig. 1. Problem definition (modified from Kiyosumi et al. [15]).

$$q_u = \frac{Q_u}{B} = s_u N_c \tag{1}$$

where q_u is the ultimate bearing stress on the footing, Q_u is the ultimate vertical force, B is the footing width, s_u is the undrained shear strength of the soil, and N_c is the dimensionless undrained bearing capacity factor.

This paper presents FE analyses for the calculation of the bearing capacity of surface strip footings on undrained clay with single and dual continuous voids. Consideration is given to the effects of void location, shape and number as well as soil rigidity and non-homogeneity. The results of the analyses are compared to other available solutions. Based on the analyses, design charts are presented in form of the undrained bearing capacity factor with respect to the dimensionless influencing parameters, and the governing failure mechanisms are discussed.

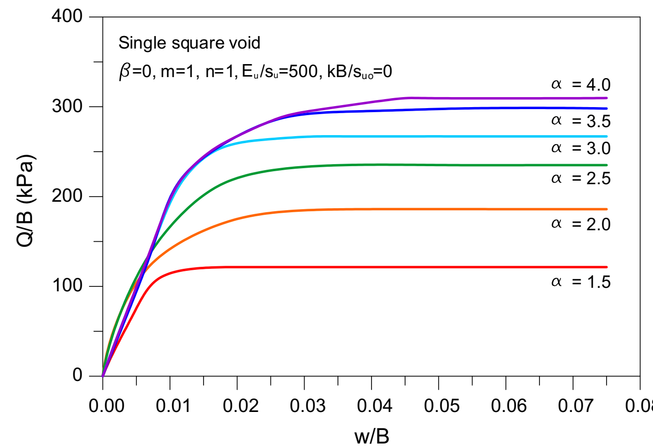

Fig. 3. Load–displacement curves for strip footing centered above single voids.

2. Problem definition

Fig. 1 illustrates the problem geometry studied and defines the key parameters. As shown in Fig. 1(a), a strip rigid footing of width B is placed on an isotropic, non-homogenous soil with a undrained Young's modulus E_u, a uniform unit weight γ, a surface undrained shear strength s_{u0}, and a rate of strength increasing with depth k. The undrained strength of the soil at a depth z is given as

$$s_u(z) = s_{uo} + kz \tag{2}$$

The undrained shear strength profile is common in normally consolidated (NC) clay, and $k = 0$ corresponds to the homogeneous clay with uniform strength. Such strength variation is quantified in terms of the nondimensional parameter kB/s_{uo}, which ranges typically between 0 and 1 for onshore applications [19,20].

The performance of a footing above voids is affected by the location, shape and number of voids [15], which are expressed through dimensionless parameters, i.e., the vertical void distance α (defined as the ratio of vertical distance from the ground surface to the

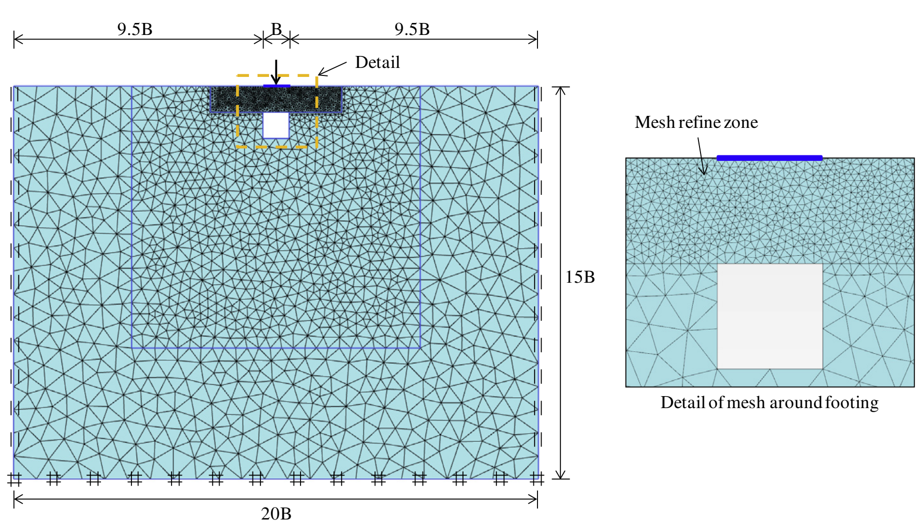

Fig. 2. Typical finite element mesh and boundary extension for soil and foundation domain.