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Undrained bearing capacity of ring foundations on two-layered clays

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ABSTRACT

This paper presents the results of a numerical investigation into the undrained vertical bearing capacity of rough ring foundations resting on two-layered clays of both homogeneous and linearly increasing shear strength profiles. Small displacement finite element predictions are compared with the available empirical, analytical and numerical solutions, and expressed in the familiar form of bearing capacity factors reflecting the coupling effects of the dimensionless parameters related to foundation internal opening, relative top layer thickness, strength difference between two layers, and strength non-homogeneity. The depth beyond which the shear strength of the bottom layer does not affect the bearing capacity, defined here as critical depth ratio, is identified. The failure mechanisms of ring foundations are also discussed in terms of the displacement pattern.

1. Introduction

In geoengineering practice, ring foundations are often utilized as bases for offshore and onshore axisymmetrical structures such as wind turbines, annular platforms, transmission towers, water tanks and silos because the foundations with internal opening are more economical than mat foundations (Bowles, 1997). The interaction of such foundations with supporting medium is affected by footing geometry as well as soil and loading conditions. A clear understanding of bearing responses for the ring foundations is indispensable to a successful design.

Several studies have been performed to predict the bearing capacity behavior of ring foundations. This has been done through using the plastic stress field approach constructed by the method of characteristics (Kumar and Ghosh, 2005), limit equilibrium theory (Karaulov, 2005, 2006), finite difference method (Zhao and Wang, 2008; Benmebarek et al., 2012a) and finite element method (Choobbasti et al., 2010; Lee et al., 2016). The laboratory test results of model ring plates in sand were reported by Ohri et al. (1997). On the other hand, some attempts have been made to analyze the geotechnical stability of ring foundations on reinforced soil. This problem was studied experimentally and numerically by Boushehrian and Hataf (2003) who explored the effects of number and spacing of geogrid reinforcement layers. El Sawwaf and Nazir (2012) investigated the bearing capacity of ring foundations subjected to eccentric loads.

Seabed sediments and natural soils usually comprise discrete layers of different thicknesses and properties, namely soil profile beneath foundations is heterogeneous. The stability for multi-layered soils is particularly more important for structures with large shallow foundations, in which the foundation loads extend to great depth below the surface. Especially, the potential for unexpected punching shear failure of offshore foundations may occur during installation in layered clays (Poulos 1988; Kim et al., 2015). The bearing capacity problems in a simple two-layered clay system have been extensively studied by numerous researchers: Button (1953) determined upper bound solutions for surface strip foundations by assuming a simple circular rupture surface. On the basis of the limit equilibrium method, Reddy and Srinivasan (1967, 1971) calculated bearing capacity factors for spread foundations resting on anisotropic clays. Semi-empirical solutions for various shapes of foundations (i.e., strip, rectangular, square and circular foundations) were proposed by Brown and Meyerhof (1969), Vesic (1973) and Meyerhof and Hanna (1978), and primarily based on experimental results. The kinematic approaches of limit analysis for strip foundations were developed by Florkiewicz (1989), Michalowski (2002) and Huang and Qin (2009), although they postulated slightly different failure mechanisms of two-layered systems. Merifield et al. (1999) employed the upper and lower bound theorems of limit analysis in conjunction with finite element (FE) to evaluate the plasticity solutions for strip foundations. Goss and Griffiths (2001) presented the bearing capacity calculations of strip

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foundations from the small displacement FE analysis, followed by the extensive works of Zhu and Michalowski (2005) and Merifield and Nguyen (2006) for circular, square and rectangular foundations. The large deformation FE analyses, simulating the continuously penetration process of strip, square and circular foundations into strong over weak clays, were suggested by Wang and Carter (2002) and Yu et al. (2011). Boulbibane and Ponter (2005) provided the collapse loads for strip foundations by means of the linear matching method. Kuo et al. (2009) assessed the feasibility of applying the artificial neural network (ANN) technique for estimating the bearing capacity of strip foundations. More recently, the influences of embedment and strength non-homogeneity on the bearing response of strip foundations were addressed by Bandini and Pham (2011) and Benmebarek et al. (2012b), respectively. Nevertheless, it can be pointed out that almost all of these studies are limited to solid foundations without any holes on two-layered clays, although the methods of analysis varied.

The objective of this study is to present calculations of undrained vertical bearing capacity factors N_c^* for ring rough foundations on two-layered clays, accounting for external-to-internal-radius ratio, relative top layer thickness, strength ratio of the two clays, and strength non-homogeneity. A numerical solution is established using a small displacement FE method. The values of N_c^* obtained in this study are compared with existing solutions from literature and the FE displacement patterns at collapse for the ring foundations are examined.

2. Problem statement

Fig. 1 illustrates the geometry and parameters of the bearing capacity problem considered. A rigid ring foundation is placed on a two-layered clay medium with horizontal ground surface. The ring foundation is denoted as external and internal radii R_0 and R_i, respectively. In this study, five external-to-internal- radius ratios (R_i/R_0=0, 0.25, 0.33, 0.5, 0.75) were taken into account, which covers most problems of practical interest (Benmebarek et al., 2012a). The foundation roughness is idealized as perfectly rough, which does not allow any relative movement at all along the soil-foundation interface. A similar assumption is used in the literature (Houlsby and Martin, 2003; Edwards et al., 2005; Merifield and Nguyen, 2006; Yu et al., 2011) for undrained bearing capacity of shallow foundations. The top layer of clay with thickness H and non-uniform undrained shear strength $s_u\,(z)=s_{u0-t}+kz$ is underlain by a clay layer of (nominally) infinite depth and non-uniform undrained shear strength $s_u\,(z)=s_{u0-b}+k(z-H)$; where s_{u0-t} and s_{u0-b} are the undrained shear strength at foundation level and top–bottom layer interface, respectively. Note that the stability of a two-layer system in which the underlying layer is infinite is often encountered in engineering practice, especially in offshore foundation and highway designs. k is the rate of increase of shear strength s_u with depth z, i.e., $k=ds_u/dz$. For a foundation of diameter D ($=2R_0$), it is convenient to quantify the degree of non-homogeneity beneath the foundation in terms of the dimensionless ratio $kD/s_{u0\text{-}t}$, accounting for values ranging from 0 (uniform) to 4 (Houlsby and Martin, 2003). It is apparent that the effect of strength non-homogeneity is especially significant for large foundations on weak clays. The strength difference between the two distinct layers is characterized by the ratio of the top layer strength to the bottom layer strength $s_{u0\text{-}t}/s_{u0\text{-}b}$. The strength ratio of the two clays varies from 0.25 to 5, indicating that $s_{u0-t}/s_{u0-b}<1$ corresponds to the cases of a soft clay over a stiff clay layer, whereas $s_{u0-t}/s_{u0-b}>1$ corresponds to the reverse. To obtain solutions to a range of the two-layered clay problem, the relative thickness of the top layer defined as the ratio of the top layer thickness to the footing diameter H/D is introduced, encompassing values of H/D varying from 0.125 to 1 (Yu et al., 2011). The specific cases of single layer (H/D=infinite) with uniform and non-uniform strength are also considered. The soil strength profiles for parametric study is visible in Fig. 2. For a two-layered clay system, the undrained bearing capacity factor N_c^* of ring foundations can then be expressed as

$$N_c^*=\frac{Q}{\pi(R_0^2-R_i^2)s_{u0-t}}=f\left(\frac{R_i}{R_0},\frac{kD}{s_{u0-t}},\frac{s_{u0-t}}{s_{u0-b}},\frac{H}{D}\right) \tag{1}$$

where Q is the vertical load given by

$$Q=2\pi q\int_{R_i}^{R_0} r\mathrm{d}r \tag{2}$$

where q is the unit bearing pressure acting on the footing and r is the radial distance of a point from the axis of symmetry.

3. Finite element analysis

Small displacement finite element analyses were carried out with the commercially available software PLAXIS version 2012 (Brinkgreve et al., 2012). The finite element model consisted of two parts: the soil and the foundation. Six-node triangular elements were used to represent soil, while foundation was composed by six-node triangular plate elements. Due to the symmetry in geometry and loading configurations, only half of the problem domain was

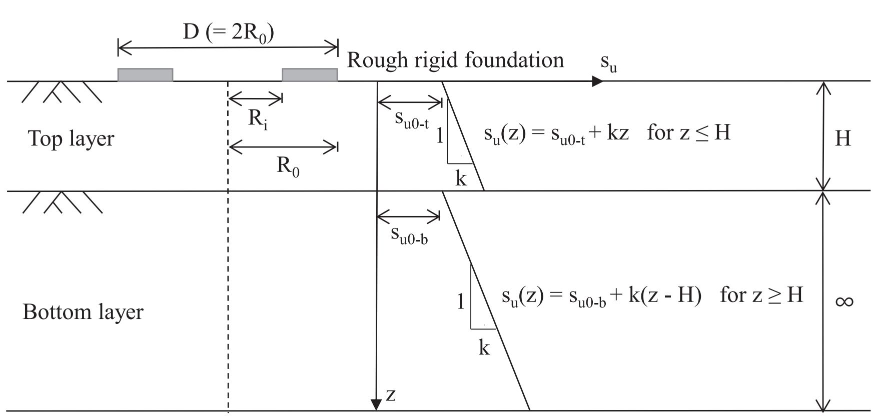

Fig. 1. Ring foundation on two-layered clays.