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Undrained bearing capacity factors for ring footings in heterogeneous soil

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ABSTRACT

This paper examines the undrained vertical bearing capacity of a ring rough footing embedded in heterogeneous soil. Stability solutions for a wide range of geometric and material combinations are obtained by small-strain finite element analysis. Design tables and charts are provided for evaluating undrained bearing capacity factors as a function of the dimensionless parameters related to footing internal opening, embedment and soil strength heterogeneity. The results from the present analysis are compared with the experimental data and existing solutions reported in the literature. The transition from shallow to deep failure modes for the ring footing is broadly discussed in terms of the displacement pattern. The undrained bearing capacity factors for different values of soil friction angle are also studied to investigate the effect of friction angle on the undrained stability of ring footings in heterogeneous soil.

1. Introduction

In engineering practice, ring footings are commonly used to support axisymmetric structures (e.g., cooling towers, storage tanks, radar stations, transmission towers, chimneys and silos) because they are more cost-effective than circular footings [1]. Such footings can vary from a relatively narrow circular beam to a solid circular mat, depending on internal opening. The behavioral characteristics of the ring footings not only depend on the footing geometry, but also on the footing embedment, footing–soil interface roughness and soil strength heterogeneity. A good knowledge of bearing capacity response for ring footings is necessary for a proper design.

Although a number of studies were conducted on the geotechnical stability of circular footings by means of empirical, analytical and numerical approaches, limited attempts have been made to study the bearing capacity of ring footings. Hataf and Razavi [2] presented the results of the laboratory model tests of annular plates placed on sand and stated that the maximum unit base resistance is achieved for inside to outside radii ratio of 0.2–0.4. Kumar and Ghosh [3] determined the bearing capacity factor N_γ for both smooth and rough ring footings based on the method of characteristics. Karaulov [4] analyzed the contact pressure distribution in ring foundations using limit equilibrium theory. Zhao and Wang [5] applied the finite difference method to calculate the bearing capacity factor N_γ of smooth and rough ring footings by assuming that soil behaves as a material with an associated flow rule. Benmebarek et al. [6] explored the influence of nonassociativity in plasticity on the bearing capacity factor N_γ of the ring footings. Meanwhile, the bearing capacity problems of ring footings on reinforced soil were also taken into account by researchers. Boushehrian and Hataf [7] studied experimentally and numerically the bearing capacity of ring footings on reinforced sand as varying vertical spacing and number of reinforcement layers. El Sawwaf and Nazir [8] reported an experimental study of the performance of an eccentrically loaded model ring plates on sand with geogrid reinforcement. More recently, Naderi and Hataf [9] investigated the interference effect on the bearing capacity behavior of closed spaced ring footings on reinforced sand. Nevertheless, it can be pointed out that most works have focused on ring footings resting on cohesionless frictional soil. By contrast, the undrained bearing capacity of ring footings embedded in cohesive medium has not been discussed in the open literature.

The objective of this paper is to present calculations of undrained vertical bearing capacity factors N_c for ring rough footings accounting for inside to outside radius ratio, embedment ratio and soil heterogeneity ratio. A numerical solution is established using a small-strain finite element (FE) method. The values of N_c obtained in this study are compared with the available results from literature and the FE displacement patterns at collapse for the ring footings are demonstrated. The influence of soil friction angle on N_c is also examined.

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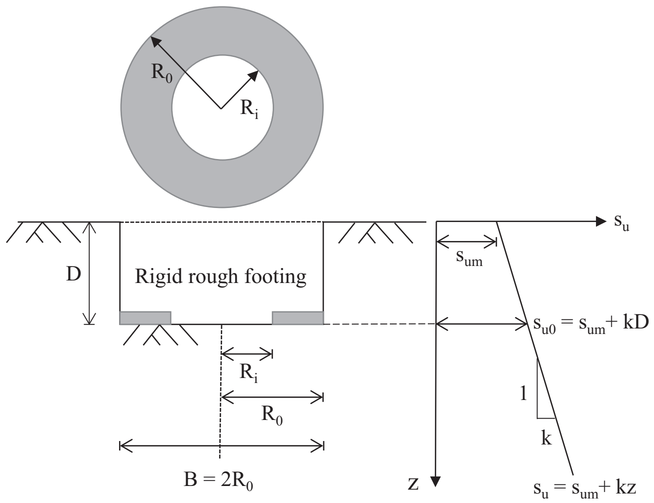

Fig. 1. Problem notation.

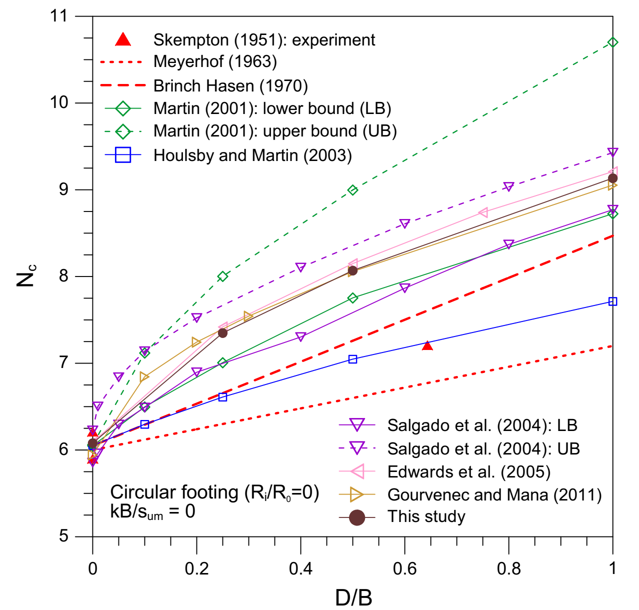

Fig. 2. Comparison of N_c values for circular footings embedded in homogenous soil.

Table 1
Undrained bearing capacity factor N_c for ring and circular footings in heterogeneous soil.

kB/s_{um}	D/B	R_i/R_0				
		0.00[a]	0.25	0.33	0.50	0.75
0[b]	0[c]	6.08	5.92	5.81	5.61	5.40
	0.25	7.35	7.20	7.01	6.66	6.26
	0.5	8.07	7.85	7.52	6.89	6.26
	1	9.14	8.33	7.73	6.90	6.26
2	0[c]	7.64	7.03	6.82	6.40	5.84
	0.25	8.76	8.03	7.77	7.31	6.70
	0.5	9.11	8.35	8.02	7.45	6.59
	1	9.59	8.61	8.09	7.27	6.48
5	0[c]	9.23	8.18	7.89	7.30	6.41
	0.25	9.36	8.43	8.14	7.63	6.96
	0.5	9.38	8.49	8.16	7.61	6.72
	1	9.58	8.58	8.18	7.35	6.54
10	0[c]	11.42	9.68	9.26	8.44	7.15
	0.25	9.73	8.68	8.37	7.82	7.09
	0.5	9.50	8.55	8.23	7.67	6.79
	1	9.50	8.55	8.20	7.40	6.57
30	0[c]	18.03	14.14	13.37	11.76	9.24
	0.25	10.00	8.89	8.58	7.99	7.21
	0.5	9.57	8.59	8.27	7.72	6.85
	1	9.56	8.58	8.24	7.42	6.58

[a] $R_i/R_0 = 0$: circular footing.
[b] $kB/s_{um} = 0$: homogenous soil.
[c] $D/B = 0$: surface footing.

Table 2
Comparison of obtained N_c values of circular footings with those available from literature.

kB/s_{um}	D/B	Circular footing ($R_i/R_0 = 0$)				
		TC	HU	HM	GM	Present
2	0	7.70	7.830	7.632	–	7.64
	0.25	–	–	7.725	–	8.76
	0.5	–	9.287	7.804	–	9.11
	1	–	–	7.984	–	9.59
5	0	–	–	9.228	9.151	9.23
	0.25	–	–	8.249	–	9.36
	0.5	–	–	8.025	9.310	9.38
	1	–	–	8.003	9.529	9.58
10	0	11.38	–	11.330		11.42
	0.25	–	–	–	–	9.73
	0.5	–	–	–	–	9.50
	1	–	–	–	–	9.50
30	0	18.70	18.600	–	–	18.03
	0.25	–	–	–	–	10.00
	0.5	–	9.560	–	–	9.57
	1	–	–	–	–	9.56

Note: TC = Tani and Craig [17] – lower bound approach; HU = Hu et al. [23] – upper bound approach; HM = Houlsby and Martin [12] – method of characteristics; GM = Gourvenec and Mana [19] – finite element analysis.

2. Problem description

Fig. 1 illustrates the bearing capacity problem of a rigid ring footing buried in a cohesive non-frictional soil. The ring footing is characterized by inside and outside radii R_i and R_0, respectively. In this study, five inside-to-outside-radius ratios (R_i/R_0 = 0, 0.25, 0.33, 0.5, 0.75) were investigated, which covers most problems of practical interest [6]. The footing–soil interface is idealized to be perfectly rough, which does not allow any relative movement at all along the footing–soil interface. The soil is considered as isotropic but heterogeneous, with the undrained shear strength s_u specified as varying linearly with depth

$$s_u = s_{um} + kz \tag{1}$$

in which s_{um} is the undrained strength at the surface, k is the strength gradient with depth z. The undrained strength at footing level is defined as $s_{u0} = s_{um} + kD$, where D is the embedment depth of the footing (Fig. 1). For shallow footings, this is realistic for embedment depths less than 100% of the footing diameter B (= $2R_0$), corresponding to $D/B \leqslant 1$ [10]. The degree of soil heterogeneity beneath the footing can be quantified by the non-dimensional ratio kB/s_{um}, indicating that the effect of heterogeneity is particularly important for huge footings on soft clay. This study encompasses the values of kB/s_{um} ranging from 0 (homogenous soil) to 30. The undrained bearing capacity factor N_c of the embedded ring footings can then be stated as

$$N_c = \frac{Q}{\pi(R_0^2 - R_i^2)s_{u0}} = f\left(\frac{R_i}{R_0}, \frac{D}{B}, \frac{kB}{s_{um}}\right) \tag{2}$$

where Q is the ultimate vertical load given by