Computers and Geotechnics 92 (2017) 169–178

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Bearing capacity of ring footings on cohesionless soil under eccentric load

Omid Sargazi, Ehsan Seyedi Hosseininia [*]

Civil Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad, Iran

ARTICLE INFO

Article history:
Received 14 May 2017
Received in revised form 6 August 2017
Accepted 8 August 2017

Keywords:
Bearing capacity
Ring footing
Eccentric load

ABSTRACT

This paper presents a study on the bearing capacity of eccentrically-loaded rough ring footings resting over cohesionless soil. To this aim, a series of 3D numerical simulations were performed using the finite difference method. In order to consider the effect of load eccentricity, reduction factor method is applied. In this method, the ratio of an eccentrically-loaded bearing capacity to the bearing capacity of the same footing under vertical load is defined. Comparison between the results of the numerical simulations with those of analytical solutions and experimental data indicates good agreement. A mathematical expression is also introduced for eccentrically-loaded ring footings.

1. Introduction

Ring footings are mostly used for supporting large and tall structures that the geometry is axisymmetric. Some examples of the ring footing applications are tower silos [1–4], oil [5] and water storage tanks [6,7], radio-television towers [4], cooling towers [8], bridge piers, and offshore structures [9,10]. The advantage of ring footings with respect to circular footings is that the amount of volume and thus the construction cost is reduced. In addition, the ring footing provides an increase in stabilizing moment arm when compared to a circular footing with the same area. Ring footing can also act as an anchorage against slip under dynamic loads [10]. The superstructures of the ring footings are usually subjected to lateral loads and moments and thus, the ring footings are to be designed under an eccentric loading condition. An offshore wind turbine situated in an icy region is an example which is imposed by large lateral loads and moments from wave, ice, and especially wind [10]. The application of ring footings can be regarded as a solution to increase the overturning stability, decrease the scouring and excessive displacements.

In comparison with strip and circular footings, there are limited researches available for the behavior of ring footings. The works can be categorized in two groups including the ring footing settlement and the ring footing bearing capacity. On the settlement of ring footings, there are analytical solutions based on elasticity and superposition principle for semi-infinite elastic soil medium. Fischer [11] and Egorov [12] examined the load-settlement response and contact pressure distribution beneath flexible and rigid ring footings. Based on numerical analysis, Naseri and Hosseininia [13] carried out numerical simulations by using finite difference method to investigate the elastic settlement of ring footings resting over an elastic half space. They examined the effect of footing embedment and rigidity as well as soil non-homogeneity on the footing elastic settlement. Results are presented in the form of graphs and corresponding mathematical expressions for settlement influence factors. On the bearing capacity of ring footings, several attempts were carried out to find appropriate analytical solutions in terms of bearing capacity factors. Kumar and Chakraborty [14] derived bearing capacity factors by using lower and upper bound theorems of the limit analysis in conjunction with finite element method. Kumar and Ghosh used the stress characteristics method to calculate the bearing capacity factor N_γ for smooth and rough rigid ring footings. Recently, by using the same approach, Gholami and Hosseininia [15] and Keshavarz and Kumar [16] derived all three bearing capacity factors for rigid ring footings. In addition, by using the numerical code FLAC, Zhao and Wang [17], Benmebarak et al. [18] and Hosseininia [19] have derived the bearing capacity factors of rigid ring footings for a range of soil friction angles. Due to the geometry of the ring footing, in all the works mentioned above, the analyses were carried out under axisymmetric condition rather than applying three-dimensional analyses. In domain of experimental studies, the behavior of rigid ring footings resting on cohesionless soils were studied by small scale laboratory or field tests [20–25]. Based on the experiments, it has been shown that the bearing capacity of the ring footing is a function of the ring diameter ratio in such a way that the bearing capacity increases up to a diameter ratio of

---

[*] Corresponding author.
E-mail address: eseyedi@um.ac.ir (E. Seyedi Hosseininia).

http://dx.doi.org/10.1016/j.compgeo.2017.08.003
0266-352X/

about 0.3–0.4 and thereafter, it decreases as the diameter ratio increases. It is again reminded that all these works only concerns the behavior of the ring footings under vertical loading condition.

By searching the literature, it can be found out that very few studies exist that focused on the effect of load eccentricity on the bearing capacity of ring footings. Elsawwaf and Nazir [26] perused the behavior of eccentrically loaded small-scale rigid ring footings in the laboratory which was rested on reinforced layered sandy soil. Zhu [27] investigated the effect of load eccentricity over rigid ring footings by means of centrifuge modeling. As expected, Zhu [27] showed that the load eccentricity reduces the bearing capacity in comparison with the centric loading condition. Based on such a brief review of all the studies mentioned above, it can be understood that more investigation is needed in order to understand the bearing capacity of ring footings under eccentric load.

In the present study, the bearing capacity of ring footings under eccentric load is investigated by numerical simulation. It is assumed that a ring footing rests on a purely cohesionless soil over the surface. The footing is rigid and it has a rough contacting surface with the soil underneath. The so called linear elastic perfectly-plastic Mohr-Coulomb model is considered for the soil constitutive model and the footing is considered as an elastic material. Three-dimensional simulations were performed in the analyses by using the numerical finite difference method. In order to evaluate the simulations, the results of the numerical simulations are compared with those of analytical and numerical solutions as well as experimental data presented in the literature. In the end, a simple formula is suggested for the assessment of bearing capacity of eccentrically-loaded ring footings based on the reduction factor method in terms of load eccentricity as well as ring diameter ratio.

2. Bearing capacity and load eccentricity

In foundation engineering practice, the footing bearing capacity with eccentric load is taken into consideration by two approaches. These approaches are effective area and reduction factor methods. In the effective area method introduced by Meyerhof [28,29], it is assumed that the dimensions of the footing are reduced such that a uniform pressure under the footing (and over the contacting soil) is imposed over the reduced effective area. This pressure represents an equivalent uniform bearing pressure and not the actual contact pressure distribution beneath the footing. This equivalent bearing pressure is multiplied by the reduced area to determine the ultimate load capacity of the footing. There are many studies in the literature that investigated the applicability of this method [e.g., 30,31–33]. Although the effective area method gives conservative result [29,34,35], it is now widely used in practice for strip, rectangular, and circular footings [5,36,37].

The effective area method is applicable for the footings where the geometry of the equivalent area can be simplified as a rectangle or a circle, whose bearing capacity equations are available. Fig. 1 indicates the concept of effective area method for a rectangular footing with length (L) and width (B), a circular footing with diameter (D) and a ring footing with outer (D_o) and inner (D_i) diameters. As shown in parts a and b of Fig. 1, the hatched area over which, an equivalent uniform pressure is applied, can be considered as an equivalent rectangle (with effective width B') or circle (with effective diameter D') and then, the bearing capacity of the equivalent footing (with the area A') is calculated. For ring footings, according to Fig. 1c, it is not possible to find a homothetic surface lying in the hatched area and thus, the effective area method is not suitable for ring footings.

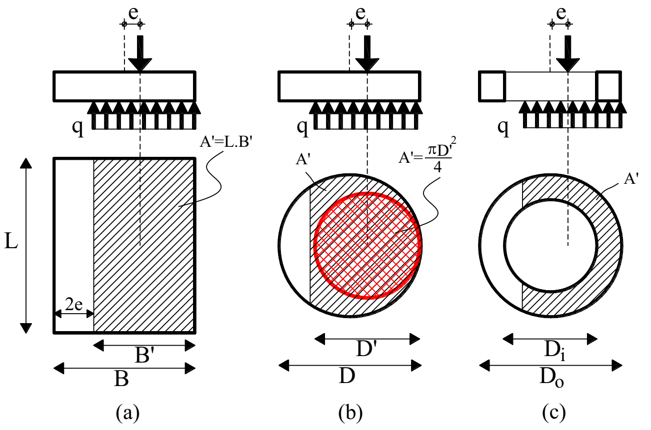

Fig. 1. Concept of effective area method in order to consider load eccentricity for: (a) rectangular footing; (b) circular footing; (c) ring footing.

As for the second approach known as the reduction factor method, the bearing capacity of eccentrically-loaded footing (q_{ult}) is calculated directly by multiplying a reduction factor (R_f) by the bearing capacity of the footing under vertical load ($q_{ult(e=0)}$):

$$q_{ult} = R_f \cdot q_{ult(e=0)} \tag{1}$$

In this method, the area of the footing is not changed and thus, the ultimate load capacity with eccentricity (P_{ult}) can be calculated similarly as $P_{ult} = R_f \cdot P_{ult(e=0)}$ where $P_{ult(e=0)}$ stands for the ultimate load of the footing with centric load. This method was initially introduced by Meyerhof [28] and now it is used for strip footings. This method was investigated experimentally [38,39] and then, it has been extended to consider footing embedment [40] as well as soil improvement effect by reinforcement layers [37]. In this method, no assumption is made for the eccentrically-loaded footing area and the effect of load eccentricity and generally, the failure mechanism is considered in the reduction factor. Since no simplified shape of footing (such as rectangle or circle) is required, this method is suitable for studying the bearing capacity of ring footings with eccentric load.

The ultimate bearing capacity of a an eccentrically-loaded ring footing (q_{ult}) can be expressed in a similar form of Terzaghi's equation [19] as follows:

$$q_{ult} = cN^*_{c(e)} + q_0 N^*_{q(e)} + 0.5\gamma_s D_o N^*_{\gamma(e)} \tag{2}$$

where c is the soil cohesion, q_0 is the surcharge over the surface, γ_s is the soil unit weight and D_o is the outer ring diameter. $N^*_{c(e)}, N^*_{q(e)}$ and $N^*_{\gamma(e)}$ are bearing capacity factors in which the shape factors are included. The subscript (e) denotes the consideration of load eccentricity. In the case of a ring footing embedded on the surface of a cohesionless soil, the bearing capacity of a ring footing is simplified into:

$$q_{ult} = 0.5\gamma_s D_o N^*_{\gamma(e)} \tag{3}$$

Based on the reduction factor method, the bearing capacity of an eccentrically-loaded ring footing can be related to that of a vertically-loaded ring footing ($q_{ult(e=0)}$) by using a reduction factor (R_f). Based on Eqs. (1) and (3), one can reach the following relationship:

$$R_f = \frac{q_{ult(e)}}{q_{ult(e=0)}} = \frac{N^*_{\gamma(e)}}{N^*_{\gamma(e=0)}} \tag{4}$$

where $N^*_{\gamma(e)}$ and $N^*_{\gamma(e=0)}$ represent the bearing capacity factors in the case of eccentric ($e \neq 0$) and centric ($e = 0$) loading conditions, respectively.