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Behavior of ring footing resting on reinforced sand subjected to eccentric-inclined loading

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ABSTRACT

Ring footings are suitable for the structures like tall transmission towers, chimneys, silos and oil storages. These types of structures are susceptible to horizontal loads (wind load) in addition to their dead weight. In the literature, very little or no effort has been made to study the effect of ring footing resting on reinforced sand when subjected to eccentric, inclined and/or eccentric-inclined loadings. This paper aims to study the behavior of ring footing resting on loose sand and/or compacted randomly distributed fiber-reinforced sand (RDFS) when subjected to eccentric (0*B*, 0.05*B* and 0.1*B*, where *B* is the outer diameter of ring footing), inclined (0°, 5°, 10°, 15°, −5°, −10° and −15°) and eccentric-inclined loadings by using a finite element (FE) software PLAXIS 3D. The behavior of ring footing is studied by using a dimensionless factor called reduction factor (RF). The numerical model used in the PLAXIS 3D has been validated by conducting model plate load tests. Moreover, an empirical expression using regression analysis has been presented which will be helpful in plotting a load-settlement curve for the ring footing.

1. Introduction

Ring footings are suitable for the structures which are circular in plan and all the external or internal forces are transferred through their wall into the foundation before they get transferred into the ground. Tall transmission towers, chimneys, silos and oil storages are suggested to be founded on ring foundations. As ring footings are more suitable for these types of structures, which are supposed to be taller than the existing structures around them, these structures are more susceptible to horizontal loads/forces like wind loads. The ring foundation has to bear not only the vertical loads but also the horizontal loads. The combination of horizontal and vertical loads acting on the structure will result in an inclined load. Moreover, the location of horizontal load (centroid) anywhere along the height of the structure may produce eccentricity of the resultant load's point. Hence, ring footings can be subjected to both eccentric and/or inclined loadings. Many investigators have studied the behaviors of footings resting on unreinforced and/or reinforced soil beds, other than ring footings subjected to eccentric and inclined loadings (Meyerhof and Hanna, 1978; Sastry and Meyerhof, 1987; Saran and Agarwal, 1989, 1991; Taiebat and Carter, 2002; Hjiaj et al., 2004; Patra et al., 2006; El Sawwaf, 2007, 2009; Saran et al., 2007; Jao et al., 2008; Behera et al., 2013; Ornek, 2014; Badakhshan and Noorzad, 2015, 2017a, b). From their studies, one can see that as the eccentricity of the load increased, the bearing capacity of the footing decreased significantly, and more tilting of footing was also observed. Reinforcing the soil, however, can improve the bearing capacity of footing, and reduce the settlement of footing.

The majority of experimental, numerical and/or analytical studies conducted on ring footings resting on reinforced and/or unreinforced soil beds merely focused on concentric loading (Bowles, 1987; Al-Sanad et al., 1993; Ismael, 1996; Boushehrian and Hataf, 2003; Laman and Yildiz, 2003, 2007; Kumar and Ghosh, 2005; Zhao and Wang, 2008; Lee and Eun, 2009; Benmebarek et al., 2012; Naderi and Hataf, 2014; Kumar and Chakraborty, 2015; Naseri and Hosseininia, 2015; Lee et al., 2016; Keshavarz and Kumar, 2017; Sharma and Kumar, 2017a). Bowles (1987) used finite element (FE) method to calculate the bearing capacity and settlement of ring footing. Laman and Yildiz (2003) conducted model tests on ring footing resting on geogrid-reinforced sand. It was concluded that the ring footing with ratio of inner to outer radius of ring (r_i/r_o = 0.3), which gave similar results as that of full circular footing,

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can be a good option from the economic point of view in practical applications. Zhao and Wang (2008) calculated the bearing capacity factor Nγ for ring footings with different radius ratios using finite difference method. More recently, Keshavarz and Kumar (2017) used the stress characteristics method to obtain the bearing capacity factors N_c, N_q and N_γ as functions of internal friction angle (ϕ) of soil and r_i/r_o of ring footing. From the literature review, it has been found that the optimum r_i/r_o value of ring footing which behaves similar or better performance than circular footing lies in the range of 0.2–0.4, which is not a unique value.

Very limited effort has been made to understand the behavior of ring footing subjected to eccentric loading (El Sawwaf and Nazir, 2012). El Sawwaf and Nazir (2012) experimentally studied the behavior of eccentrically loaded ring footing resting on a compacted replaced geogrid-reinforced sand layer that overlies an extended loose sand layer. It was concluded that the reinforcement not only reduced the depth of replaced sand, but also increased the bearing capacity of eccentrically loaded ring footing significantly.

Hence, there is a need to study the effects of load eccentricity and inclination on the response of ring footings. This paper aims at studying the behavior of ring footing, resting on unreinforced and/or fiber-reinforced sand beds, when subjected to concentric, eccentric and inclined loadings using FE package PLAXIS 3D. Moreover, by replacing the loose sand up to some depth with compacted randomly distributed fiber-reinforced sand (RDFS) (fibers distributed randomly in the soil to obtain a homogeneous soil-fiber mixture), the influence of sand reinforcement on the behavior of ring footing can be studied. Ring footing used in this study has radius ratio (ri/ro) of 0.4, with outer and inner radii of 150 mm and 60 mm, respectively. Fiber percentage and depth of reinforced sand used in this study are 1% and 1B, respectively, where B is the outer diameter of ring footing. Both parameters are kept constant, because the effect of these parameters on ring footing subjected to concentric loading only has already been documented (Sharma and Kumar, 2017a, b). The load eccentricities of 0B, 0.05B and 0.1B, and inclinations of 0°, 5°, 10°, 15°, −5°, −10° and −15°, are used in this study. Furthermore, an empirical expression is developed using regression technique which will be useful in plotting load-settlement curve for eccentric, inclined and/or eccentric-inclined loaded ring footings. Finally, the numerical results are validated with the model plate load test results.

2. Load application, sign conventions and definitions for load inclination and tilting

Fig. 1a shows the sign conventions for measuring the resultant load (Q_r) inclination with respect to the Z-axis. Load inclination is positive when it is measured anticlockwise and negative when it is clockwise with respect to the Z-axis, as shown in Fig. 1a. The ratio of difference between settlements at opposite sides to width of the footing is taken as the tilt of the footing (Fig. 1b).

In order to apply vertical loads to the ring footing, uniformly distributed load is converted into multiple closely spaced point loads and then applied in a circular and symmetrical fashion, as shown in Fig. 2. Similarly, load inclination and eccentricities are given to these multiple closely spaced point loads to study their effects on the behaviors of ring footings.

3. Numerical study

Numerical study of ring footings resting on unreinforced and/or fiber-reinforced sand beds is carried out using FE package PLAXIS 3D. The width of the soil bed is taken as five times the footing width, and the depth is taken as three and a half times the footing width. Footing and soil bed model used in the FE analysis is shown in Fig. 3, in which RD_1 is the relative density of top RDFS layer, and RD_2 is the relative density of bottom unreinforced sand layer.

PLAXIS is designed for the two- or three-dimensional analyses of deformation, stability and groundwater flow in geotechnical engineering. Geotechnical applications require advanced constitutive models for the simulation of the nonlinear, time-dependent, and anisotropic behaviors of soils and/or rocks. Although the

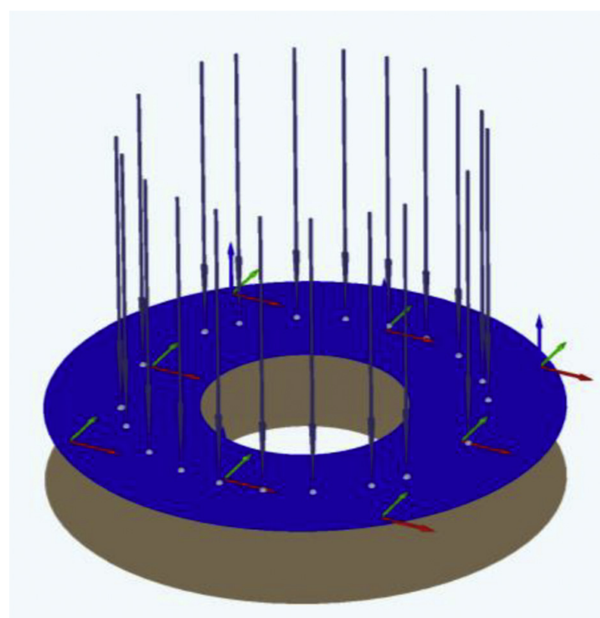

Fig. 2. Multiple closely spaced point loads applied on ring footing.

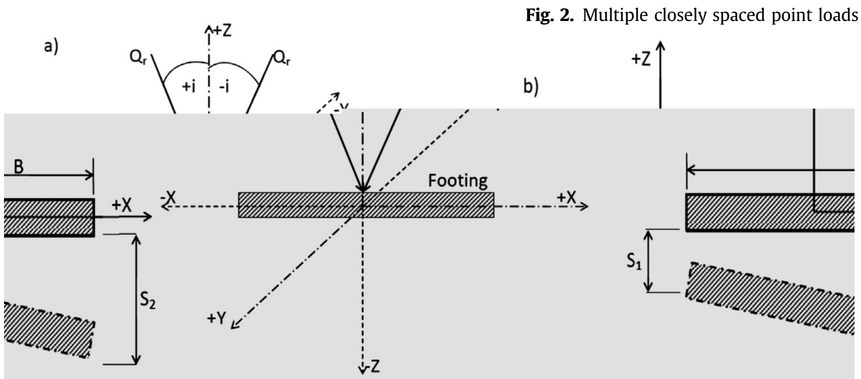

Fig. 1. Definitions for (a) load inclination and (b) footing tilt.

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