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Bearing capacity of circular foundations reinforced with geogrid sheets

Manash Chakraborty, Jyant Kumar*

Indian Institute of Science, Civil Engineering Department, Bangalore, India

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Abstract

The ultimate bearing capacity of a circular footing, placed over a soil mass which is reinforced with horizontal layers of circular reinforcement sheets, has been determined by using the upper bound theorem of the limit analysis in conjunction with finite elements and linear optimization. For performing the analysis, three different soil media have been separately considered, namely, (i) fully granular, (ii) cohesive frictional, and (iii) fully cohesive with an additional provision to account for an increase of cohesion with depth. The reinforcement sheets are assumed to be structurally strong to resist axial tension but without having any resistance to bending; such an approximation usually holds good for geogrid sheets. The shear failure between the reinforcement sheet and adjoining soil mass has been considered. The increase in the magnitudes of the bearing capacity factors (N_c and N_γ) with an inclusion of the reinforcement has been computed in terms of the efficiency factors η_c and η_γ. The results have been obtained (i) for different values of ϕ in case of fully granular ($c=0$) and $c-\phi$ soils, and (ii) for different rates (m) at which the cohesion increases with depth for a purely cohesive soil ($\phi=0^\circ$). The critical positions and corresponding optimum diameter of the reinforcement sheets, for achieving the maximum bearing capacity, have also been established. The increase in the bearing capacity with an employment of the reinforcement increases continuously with an increase in ϕ. The improvement in the bearing capacity becomes quite extensive for two layers of the reinforcements as compared to the single layer of the reinforcement. The results obtained from the study are found to compare well with the available theoretical and experimental data reported in literature.

Keywords: Bearing capacity; Circular footing; Limit analysis; Finite elements; Plasticity; Reinforcement

1. Introduction

Various forms of the reinforcement layers, such as geotextiles, geogrids and galvanized steel strips are often embedded in weak foundation soils primarily (i) to reduce footing settlements, and (ii) to increase the ultimate bearing capacity of foundations. The usage of the reinforcements in a soil medium became especially popular after the pioneering work of Vidal (1966). Subsequently, for assessing the effect of the reinforcements on load carrying capacity and settlement of the foundations, a number of researchers have performed extensive studies by using a series of models tests (Binquet and Lee, 1975; Fragaszy and Lawton, 1984; Guido et al., 1986; Khing et al., 1993; Omar et al., 1993; Das and Omar, 1994; Adams and Collin, 1997; Abu-Farsakh et al., 2013) and different computational approaches (Asaoka et al., 1994; Otani et al., 1998; Yu and Sloan, 1997; Huang and Hong, 2000; Blatz and Bathurst, 2003; Michalowski, 2004; Deb et al., 2007; Chakraborty and Kumar, 2012; Miyata and Bathurst, 2012;

*Corresponding author.
E-mail addresses: manasrcr@civil.iisc.ernet.in (M. Chakraborty), jkumar@civil.iisc.ernet.in (J. Kumar).
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Asakereh et al., 2013; Kumar and Sahoo, 2013). These studies are generally meant for reinforced strip foundations. In the recent past, a few experimental and analytical studies have also been undertaken to examine the behavior of circular footings placed on reinforced soil media (Boushehrian and Hataf, 2003; Basudhar et al., 2007; Sireesh et al., 2009; Lovisa et al., 2010; Chakraborty and Kumar, 2012; Lavasan and Ghazavi, 2012; Ornek et al., 2012; Demir et al., 2013). Boushehrian and Hataf (2003) have performed a series of laboratory tests, along with a numerical analysis, to examine the effect of the depth of the first layer of the reinforcement, vertical spacing and number of reinforcement layers on the bearing capacity of foundations. Basudhar et al. (2007) have conducted an experimental study for circular footings resting on sand reinforced with geotextiles. Sireesh et al. (2009) have investigated the inclusion of geocell reinforced sand mattress in a clay medium for a circular foundation. Lovisa et al. (2010) have experimentally investigated the potential benefit of prestressing the geotextiles layer in a reinforced soil circular foundation. Chakraborty and Kumar (2012), by using the lower bound theorem of the limit analysis in conjunction with finite elements and linear optimization, have determined the bearing capacity of a circular foundation placed over soils which are embedded with a single layer of horizontal circular reinforcement sheet. Demir et al. (2013) have carried out experimental and numerical investigations, by using Plaxis 3D, for determining the bearing capacity of a circular footing resting over granular fill reinforced with geogrid sheet overlying natural clay deposit. In the present research, the bearing capacity of a circular foundation embedded with single and two horizontal layers of the reinforcements in the form of circular geogrid sheets, has been determined by using the upper bound finite elements limit analysis in combination with linear optimization. The upper bound formulation, to incorporate the inclusion of the reinforcement sheets in the analysis, has been implemented from the work of Kumar and Sahoo (2013) for strip foundations on the basis of finite elements and linear optimization. Similar to the study of Kumar and Sahoo (2013), the circular reinforcement sheets in the present analysis are assumed to be structurally strong to resist axial tension but these reinforcements are assumed not to have any resistance to bending. The critical depths of the reinforcement layers, both for single and two layers of reinforcement sheets have been computed for different cases. Corresponding to the critical depths of the reinforcement sheets, the optimum diameter of the circular reinforcement sheet has also being evaluated. The results obtained from the analysis have been compared with that available from literature. The nodal velocity patterns have also been examined for a few typical cases.

2. Problem statement

A rigid rough circular footing of diameter, d, is placed over a soil mass reinforced with either a single or a group of two layers of horizontal circular reinforcement sheets. The point of the application of the resultant load (Q) coincides with its axis of the footing. The ground surface is horizontal without any external surcharge pressure. The soil mass is assumed to be homogenous, isotropic, perfectly plastic, and it follows an associated flow rule and the Mohr–Coulomb's failure criterion; it is known that the Mohr–Coulomb criterion is generally accepted as a good approximation for modeling the failure of soils (Abbo and Sloan, 1995; Davis and Selvadurai, 2002). Fig. 1(a) depicts the positions of the reinforcements sheets in a soil medium. The single layer reinforcement sheet is assumed to be placed at a depth h from the ground surface. In the case of two layers of reinforcements, the upper sheet is placed at a depth h_1 from ground surface, and the vertical spacing between the two layers of the reinforcement is equal to h_2. It is required to compute the ultimate bearing capacity of the foundation due to an inclusion of the reinforcement sheet(s). It is also intended to determine the critical positions of reinforcements so that the increase in the bearing capacity, with the usage of the reinforcements, becomes always the maximum. Corresponding to the critical depths, it is also aimed to find the optimum diameter (D_{opt}) of the circular reinforcements.

Three different types of soil media have been separately considered for doing the analysis, these are: (i) fully granular soil ($c=0$), (ii) cohesive frictional soil, and (ii) fully cohesive soil ($\phi=0^{\circ}$) with an additional provision to account for an increase in the value of cohesion with depth. Bishop (1966) found that for saturated normally consolidated and lightly over consolidated clays, the cohesion of soil mass under undrained condition increases almost linearly with depth. Therefore, in the case of a purely cohesive soil ($\phi=0$), the cohesion of soil mass at any depth (z) below the ground surface is defined by means of the following expression:

$$c = c_0 + \frac{m c_0 z}{d} \quad (1)$$

where (i) c and c_0 are the values of soil cohesion at a depth z and along ground surface, respectively, and (ii) m is a non-dimensional factor which indirectly defines the rate at which the cohesion increases with depth.

3. Assumptions and modeling of soil-reinforcement interference

The reinforcement sheets are assumed to have sufficient resistance to axial tension without any structural failure (breakage), but these reinforcements are assumed not to offer any resistance to bending. It needs to be mentioned that the reinforcement sheets in the form of geogrids and geotextiles do not have substantial resistance against bending (Boushehrian and Hataf, 2003). The tensile resistance of the geogrid sheet is usually much greater than that of geotextile (Lawson and Kempton, 1995), the present analysis will, therefore, remain generally applicable to soils that are reinforced with geogrid sheets; it is noted from the available literature that the axial tensile resistance of the reinforcement sheets varies approximately between (i) 26 kN/m–105 kN/m for geogrid sheets (Koerner, 1994; Demir et al., 2013; Chehab et al., 2007,