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Research Paper

Bearing capacity computation for a ring foundation using the stress characteristics method

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ABSTRACT

The stress characteristics method (*SCM*) has been used to compute the bearing capacity of smooth and rough ring foundations. Two different failure mechanisms for a smooth footing, and four different mechanisms for a rough footing have been considered. For a rough base, a curvilinear non-plastic wedge has been employed below the footing. The analysis incorporates the stress singularities at the inner as well as outer edges of the ring footing. Bearing capacity factors, N_c, N_q and N_γ are presented as a function of soil internal friction angle (ϕ) and the ratio (r_i/r_o) of inner to outer radii of the footing.

1. Introduction

Ring foundations are usually employed for different structures such as bridge piers, transmission towers, TV antennas, chimneys, and water storage tanks. As compared to solid circular foundations, only limited investigations seem to have been carried out to evaluate the bearing capacity of ring footings. Saha [1] and Boushehrian and Hataf [2] performed small scale model tests to find the bearing capacity of ring footings on sands. Kumar and Ghosh [3] used the stress characteristics method (*SCM*) to calculate the bearing capacity factor N_γ for smooth and rough ring foundations on sand. However, in this approach, the stress singularities at the inner and outer edges of the ring were not simulated, and the variation of the friction angle along the interface of the footing and underlying soil mass was assumed in an approximate manner. On the basis of FLAC and by assuming an associative flow rule, Zhao and Wang [4] computed the bearing capacity factor N_γ for smooth and rough ring foundations on sands. Benmebarek et al. [5] also used FLAC to compute N_γ for smooth and rough ring foundations for both associative and non-associative flue rules. Kumar and Chakraborty [6] employed the lower and upper bound finite elements limit analysis for evaluating the bearing capacity factors N_c, N_q and N_γ for ring foundations. Recently, under undrained condition, the bearing capacity factor N_c was computed by (i) Remadna et al. [7] by using FLAC, and (ii) Lee et al. [8,9] by using the finite element code PLAXIS.

The *SCM* is often implemented to compute quite accurate solutions for different geotechnical stability problems [10]. In the present research, by using the *SCM*, a rigorous numerical analysis has been performed by duly incorporating the stress singularities at the inner as well as the outer edges of the ring footing to establish the variation of the bearing capacity factors N_c, N_q and N_γ for both smooth and rough ring foundations as a function of (i) internal frictional angle, and (ii) the ratio of inner to outer radii of the footing. The solution procedure explores different possible types of failure mechanisms to obtain the results. Slip lines patterns for different cases have also been drawn. The results obtained from the analysis have been compared with the different solutions available in literature.

2. Governing equations along two families of stress characteristics

Fig. 1(a) can be referred for the definition of various stress variables. Following the Harr-Von Karman hypothesis, the value of σ_θ has been assumed to be equal to minor and major principal stresses corresponding to outward and inward mechanisms, respectively (Fig. 1b). An outward mechanism refers to the one in which the horizontal movements of soil mass occur away from the axis of symmetry, and in the inward collapse mechanism, the horizontal movement of the soil mass takes place mainly towards

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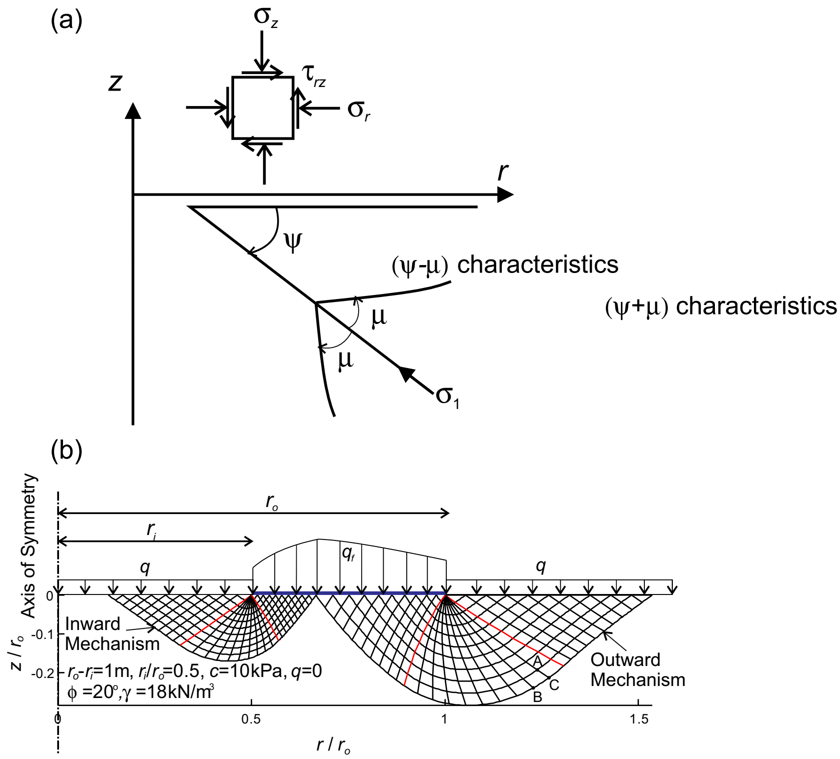

Fig. 1. (a) Definitions of stress components and stress characteristics; (b) vertical normal stresses-along ring footing, free surface inside ring and ground surface involving inward and outward mechanisms.

the axis of symmetry. By using the Mohr-Coulomb yield criterion, the stress components σ_r, σ_z and τ_{rz} are written in terms of two variables, namely, p and ψ, as given herein:

$$\sigma_r = p(1 + \sin\phi)\cos 2\psi + c\cos\phi\cos 2\psi \tag{1a}$$

$$\sigma_z = p(1 - \sin\phi)\cos 2\psi - c\cos\phi\cos 2\psi \tag{1b}$$

$$\tau_{rz} = (p\sin\phi + \cos\phi)\sin 2\psi \tag{1c}$$

where (i) $p = (\sigma_r + \sigma_z)/2$ and (ii) c and ϕ refer to cohesion and internal friction angle of soil mass, respectively, and (iii) ψ represents the angle between the positive r axis and the major principal stress direction (σ_1) as shown in Fig. 1(a). By combining equilibrium and failure conditions, the equations which are applicable along two different families of the stress characteristics are established. These equations are given as follows:

Along the $(\psi + \mu)$ characteristics:

$$\frac{\mathrm{d}z}{\mathrm{d}r} = \tan(\psi + \mu) \tag{2a}$$

$$\sin 2\mu \mathrm{d}p + 2(p\sin\phi + c\cos\phi)\mathrm{d}\psi = (\sin 2\mu \mathrm{d}r - \cos 2\mu \mathrm{d}z)f_r + (\cos 2\mu \mathrm{d}r + \sin 2\mu \mathrm{d}z)f_z \tag{2b}$$

Along the $(\psi - \mu)$ characteristics:

$$\frac{\mathrm{d}z}{\mathrm{d}r} = \tan(\psi - \mu) \tag{3a}$$

$$-\sin 2\mu \mathrm{d}p + 2(p\sin\phi + c\cos\phi)\mathrm{d}\psi = -(\sin 2\mu \mathrm{d}r + \cos 2\mu \mathrm{d}z)f_r + (\cos 2\mu \mathrm{d}r - \sin 2\mu \mathrm{d}z)f_z \tag{3b}$$

where $f_r = -\frac{\sigma_r - \sigma_\theta}{r}$; $f_z = -\gamma - \frac{\tau_{rz}}{r}$; γ is the unit weight of soil mass; and $\mu = (\pi/4 - \phi/2)$. In the *SCM*, each point involves four basic variables, which are, r, z, p and ψ. These four variables at any point C can be found numerically by using the finite difference technique on the basis of Eqs. (2) and (3) which are applicable along two different families of the stress characteristics (refer to Fig. 1b). Corresponding to the previously established states of stress at the points A and B, a trial and iterative procedure is used to establish the point C and its state of stress. Computations are first performed by using the forward difference technique and later on with the central difference technique. This procedure is repeated until the difference between the values of the associated variables between the current and previous steps becomes almost negligible. Further details about the implementation of the *SCM* can be found in [11].

3. Problem definition and stress boundary conditions

Fig. 1(b) shows the geometry of the problem. The inner and outer radii of the ring footing are indicated by r_i and r_o, respectively. The same uniform surcharge q is applied on the inner as well as outer free surface. The ultimate bearing stress beneath the footing is indicated by q_f. Along the ground surface as well as for the free surface inside the ring, the value of the normal stress σ_z becomes equal to q and the shear stress (τ_{rz}) is zero; the major principal stress directions along these boundaries become accordingly horizontal. By using the Mohr-Coulomb failure criterion, the state of stress on the ground surface as well as along the inner free surface of the ring becomes fully known, and the value of p will be given by:

$$p_0 = (q + c\cos\phi)/(1 - \sin\phi) \tag{4}$$

Along the footing-soil interface of the ring, the following stress boundary conditions need to be satisfied:

$$|\tau_{rz}| \leqslant (c/\tan\phi + \sigma_z)\tan\delta \tag{5}$$

It should be mentioned that $\delta = 0$ for a perfectly smooth base, and $\delta = \phi$ for a perfectly rough base. In the present analysis, computations have been performed only for these two extreme values of δ, namely, 0 and ϕ.