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Elastic settlement of ring foundations

Mojtaba Naseri, Ehsan Seyedi Hosseininia*

Department of Civil engineering, Faculty of Engineering, Ferdowsi University of Mashhad, PO Box 91775-1111, Mashhad, Iran

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Abstract

In this paper, numerical computations using the finite difference method are carried out in order to investigate the settlement of ring foundations resting over an elastic half space. The main goal of the present work is to introduce a closed form solution for calculating elastic settlement of ring foundations. The settlement calculation of a ring footing is achievable by definition of displacement influence factors, which is commonly used in the domain of elasticity theory. The influence factors obtained in this study address the ring geometry, footing stiffness, footing embedment, and the soil non-homogeneity by which it is assumed that the soil elastic modulus increases linearly with depth. Computational results are presented in the form of graphs and correspondent mathematical expressions are proposed for the influence factors, for use in practical applications in the analysis and design of ring footings. The results are also compared with the published numerical and analytical data for the influence factors of circular footings as a benchmark verification.

Keywords: Ring foundation; Displacement influence factors; Numerical modeling; Elastic settlement

1. Introduction

Shallow foundations are generally designed to satisfy bearing capacity and settlement criteria. Although the bearing capacity of shallow foundations is still of concern and it is still the subject of recent works (e.g., Baars, 2014; Chakraborty and Kumar, 2013; Lavasan and Ghazavi, 2012; Orneka et al., 2012), the settlement criterion is generally believed to be more dominant due to the level of structure performance (e.g., Killeena and McCabeb, 2014). When the settlement limit is exceeded, either the footing dimensions and the geometry must be revised or the soil must be reinforced (e.g., Abu-Farsakha et al., 2013; Lavasan and Ghazavi, 2012). In the settlement calculation of shallow foundations, it is common practice to consider the settlement as the sum of two parts including immediate (short term) and consolidation (long term) settlements. The difference between these two parts is the time occurrence of the vertical deflection under the foundation, depending on the rate of loading with respect to the soil permeability (e.g., Bensallam et al., 2014). The first one is mislabeled "elastic settlement", because elasticity theory has been generally adopted for calculation purposes. The soil behavior is not elastic or even reversible. However, elasticity theory has been widely used and accepted in the geotechnical engineering for the immediate settlement calculation due to its simplicity. By using the linear elasticity theory and assuming that the soil is isotropic (e.g., Ai et al., 2014), only two elastic Lamé coefficients, or alternatively elastic modulus and Poisson's ratio are needed. The magnitude of the settlement can be assessed practically by applying the linear elasticity theory in conjunction with displacement influence factors, which considers soil non-homogeneity and foundation parameters such

*Corresponding author. Tel.: +98 51 38805111; fax: +98 51 38763303.
E-mail address: eseyedi@um.ac.ir (E.S. Hosseininia).
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as the geometry, roughness, and stiffness. This procedure is applicable to settlement calculations for either undrained or drained loading conditions (e.g., Gibson, 1967; Poulos and Davis, 1974; Schmertmann et al., 1978).

Ring foundations are a special type of shallow foundations used to support loads of axisymmetric structures such as bridge piers, water tower structures, and silos. In comparison with circular footings, ring foundations are more suitable and economical because less material is required, and the construction is easier as well. However, there are still uncertainties about the assessment of bearing capacity and settlement of such footings.

The calculation of elastic settlement of ring foundations is rarely taken into consideration in the literature review. There are several elastic approaches that give formulations or graphs, and all of them pay attention to the simple geometries of foundations including circle and rectangle (e.g., Berardi and Lancellota, 1991; Boswell and Scott, 1975; Burland, 1970; Davis and Poulos, 1968; Mayne and Poulos, 1999; Schmertmann et al., 1978; Strak and Booker, 1997; Teferra and Schultz, 1988; Timoshenko and Goodier, 1951; Ueshita and Meyerhof, 1968b). Gazetas et al. (1985) proposed an analytical expression for estimating the vertical elastic settlement of foundations of any arbitrary solid basement shape embedded in a reasonably deep, uniform deposit. Their work was based on fitting analytical and numerical results from numerous publications in the literature. However, they declared that their approach excludes the ring footings and annular base shapes. Egorov and Nichiporovich (1961) obtained a formulation to calculate the settlement of the bed and the stress under rigid ring foundations by using Bessel's function of the first order. Fischer (1957) presented a solution for the settlement of a flexible ring plate on an elastic isotropic half-space. The solution gives vertical settlement of inner and outer edges of the ring plate by introducing influence factors in terms of the radii ratio. The latter two cases considers the footing rigidity as its extreme limit, i.e., perfectly rigid or flexible. In addition, it was assumed that the footing rests over the ground surface and the effect of embedment is not taken into consideration. Recently, Choobbasti et al. (2010) have modeled the settlement of ring footings using finite element method by considering an elasto-plastic analysis.

In domain of linear elastic problems with homogeneity and uniformity in soil characteristics, the deformation and stress distribution under a ring foundation can be derived by using the formulations of axisymmetric stress-strain relationships (e.g., Ahlvin and Ulery, 1962) in addition to the superposition principle. However, this is not practical since it requires a large volume of mathematical manipulations. Instead, it is more practical to apply numerical modeling using numerical methods such as the finite element method (FEM) or finite difference method (FDM). Alternatively, it is possible to use closed form solutions obtained from numerical and analytical approaches. The present paper investigates the settlement of ring foundations by applying FDM.

The objective of this study is to derive a general expression for the settlement of ring foundations in which the effects of geometry (inner to outer radii ratio), stiffness, and embedment of the footing as well as soil non-homogeneity are included by introducing corresponding displacement influence factors. To achieve this objective, a number of numerical models are performed and mathematical relations of influence factors are derived based on curve fitting.

2. Elastic settlement analysis

Elastic settlement calculation using displacement influence factors has the general form (Poulos and Davis, 1974):

$$\rho = \frac{qB}{E_s} I \tag{1}$$

where ρ is the foundation settlement; q is the applied stress; B means the foundation width; E_s stands for the equivalent elastic soil modulus; and I is the displacement influence factor. In order to obtain the displacement influence factors, rigorous solutions are needed based on the establishment of equilibrium equations, continuity equations, constitutive relationships, required kinematics, and finally solving complex integrals (Gibson, 1967; Strak and Booker, 1997; Ueshita and Meyerhof, 1968a). A great variety and number of solutions exist in the literature for different governing assumptions, foundation geometries, and specific conditions, such as foundation rigidity and soil stiffness variation. A compilation of rigorous elastic solutions can be found in the works by Poulos and Davis (1974) and Teferra and Schultz (1988).

The elastic settlement at the center point of a uniformly loaded circular footing with diameter D is given as follows (Brown, 1969a, 1969b):

$$\rho_{circle}^{center} = \frac{qD(1-\nu^2)}{E_s} I \tag{2}$$

where one has I=1 and $\pi/4$ for flexible and rigid footings, respectively. ν is the soil Poisson's ratio. Mayne and Poulos (1999) proposed a more general form of expression for the settlement of the center point of a circular foundation by considering the multiplication of several influence factors considering foundation rigidity (I_F), embedment (I_E), and soil non-homogeneity (I_G). The latter influence factor corresponds to the case where the soil modulus varies linearly with depth. The calculation of the influence factor I_G was based on the summation of unit strains of sub-layers calculated from incremental vertical and radial stress change below the center of the circular footing, while the other two influence factors were addressed by approximate modifier terms obtained from prior finite element studies published in the literature.

In the present study, the same approach used by Mayne and Poulos (1999) is taken into consideration and a general mathematical form is introduced for the elastic settlement of a ring footing. Similar to circular footing, a mathematical expression is initially derived for the maximum settlement of a ring footing and then, the magnitude of the settlement at the inner and outer edges of the ring footing are introduced.

Consider that the geometry of a ring footing is defined as the ratio of the inner to outer ring radii, i.e., $n=r_i/r_o$. This footing