Numerical Study of Modulus of Subgrade Reaction in Eccentrically Loaded Circular Footing Resting

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***Abstract*—This article is an attempt to present a numerically study of the behaviour of an eccentrically loaded circular footing resting on sand to determine its ultimate bearing capacity. A surface circular footing of diameter 12 cm (D) was used as shallow foundation. For this purpose, three dimensional models consist of foundation, and medium sandy soil was modelled by ABAQUS software. Bearing capacity of footing was evaluated and the effects of the load eccentricity on bearing capacity, its settlement, and modulus of subgrade reaction were studied. Three different values of load eccentricity with equal space from inside the core on the core boundary and outside the core boundary, which were respectively e=0.75, 1.5, and 2.25 cm, were considered. The results show that by increasing the load eccentricity, the ultimate load and the modulus of subgrade reaction decreased.

***Keywords*—Circular foundation, eccentric loading, sand, modulus of subgrade reaction.

I. Introduction

THE bearing capacity of foundations has always been one of the subjects of major interest in soil mechanics and foundation engineering. Foundations in addition to vertical loads are subjected to horizontal seismic and wind forces, particularly those with industrial application. These forces result in load eccentricity and bearing capacity reduction of foundations. High silos, refinery towers, wind turbines, chimneys, and cooling towers are such structures that circular foundation is more economical than the other forms because it can accommodate to reverse wind and earthquake direction due to its symmetry. Meyerhof [1] studied the behavior of rectangular footing with eccentricity loading and suggested the concept of effective width. Meyerhof [1] assumed that the contact pressure decreases linearly from toe to heel, when subjected to a loading with eccentricity (e). According to this concept, the bearing capacity of a strip foundation (with width B) can be determined by assuming that the load acts centrally along the effective contact width (B′) that is defined as B′=B-2e. Highter and Anders [2] suggested non-dimensional curves for calculation the effective area A′ and the effective width B′ as shown in Fig 1. Several researchers studied the behavior of square and rectangular foundations with eccentric loading [3]-[8]. Sawwaf and Nazir studied the behavior of eccentrically loaded small scale ring footings resting on sand [9]. They reported that the behavior of an eccentrically loaded ring footing significantly improved with an increase in the depth and relative density of the replaced compacted sand layer.

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Boushehrian and Hataf [10] studied the behaviour of circular footing on sand and reported that circular foundation is more suitable and economical for axi-symmetric structures. Basudhar et al. [11] carried out the numerical analysis in reinforced circular footing with geotextile, and results show that the settlement decreases by increasing the number of geotextaile.

To investigate the effect of eccentric loading on a circular footing resting on sand, the properties of materials used in the model are described in Table I.

The numerical studies mentioned above focused on eccentrically loaded circular foundation resting on medium sand. The present study focuses on the effects of different load eccentricities, on the bearing capacity, settlement and modulus of subgrade reaction of the circular footing resting on sand bed.

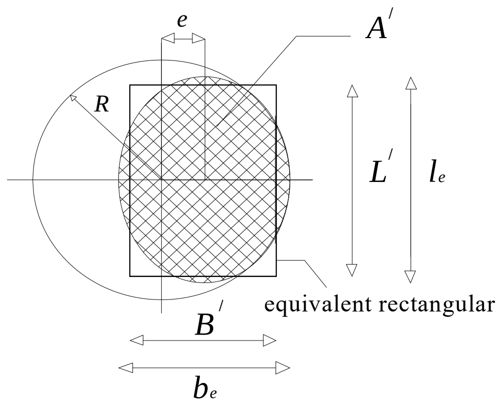

Fig. 1 Effective area method [2]

TABLE I
Material Properties

Properties	soil	foundation
Young’s Modulus (MPa)	400	200000
Poisson’s Ratio (υ)	0.28	0.2
φ (deg)	38°	-
Cohesion (Mpa)	1	-

II. Finite Element Strategy

The finite element program ABAQUS [12] was used to model the tests of circular footing on sand. For modeling the yielding of frictional material (sand) in this study, the perfectly-elastic plastic Drucker-Prager model was used. For the circular footing, all of the numerical analyses were carried out in three-dimensional space. The boundary conditions were chosen such that the displacement of the horizontal boundary is restricted in all directions, while vertical boundaries are restricted horizontally and are free to move in vertical direction. Mesh was developed by using linear brick elements for the rigid foundation and soil. Relatively fine mesh is occupied near the surface while a coarser mesh was used for further distance from the foundation. Analysis was performed under displacement controlled method. The geometry of a typical finite element model for the analyses is shown in Fig. 2.

Most of the structures involve some type of structural element with direct contact with ground. Also, soil-structure interaction has considerable effect on result, but conventional structural design methods neglect the soil- structure interaction effects. Therefore, the interaction should be considered. Numerous studies [13]–[16] show that it has conventionally been considered that soil-structure interaction has a beneficial effect on the seismic and static response of a structure. These studies show the simplified manner to calculate interaction. A limited number of studies [17]–[20] have been conducted on soil–structure interaction effect considering three-dimensional space frames. The studies clearly indicated that a two-dimensional plane frame analysis might substantially overestimate or underestimate the actual interaction effect in a space frame. From these studies, it becomes obvious that the consideration of the interaction effect significantly alters the design force quantities.

Friction plays an important role in the interaction effects between foundation and soil. Sliding of the foundation over its soil which occurs when the lateral inertial force (base shear) exceeds the static friction force is prevented by friction. Friction is an integral part of the contact algorithms of ABAQUS and it is based on a Coulomb formulation, where the magnitude of the friction force is proportional to the normal force, but its direction is always opposite to that of the sliding velocity.

Jeong et al. [21] declared that the interface friction coefficient for granular soil varies up to 0.6. In this study, the friction coefficient between sand and foundation is 0.5.

The footing used in the model was circular with 12 cm diameter and 1.5 cm thickness that was assumed to be a rigid foundation. The diameter of circular footing was selected about 0.2 soil cubic dimensions to assure that failure planes under footing would be within the cubic limit. Thus, the dimension of the soil cubic is 60x60x60 cm. For eccentricity loading of circular foundations, core boundary according to (1) is (R/4), where q′ is the contact pressure under edge of footing, V is the centric load, A′ is the area of footing, M is the moment, y is the largest distance from the center, and I is the moment of inertia. Loading inside the core boundary, puts the whole footing area under pressure. Outside the core boundary, the footing edge is subjected to uplift pressure and footing arises up the soil. The loading on the core boundary is causing the pressure's edge to become zero. In this study, three eccentricity loadings were selected: R/8=0.75 cm, R/4=1.5 cm, and 2.25 cm for inside the core boundary, on the core boundary, and outside the core boundary, respectively. The footing core and eccentricity loaded locations are demonstrated in Fig. 3.

The footing was placed on top of the sand and loading applied with 1 mm/min velocity. Loading was continued until 40 mm footing settlement, when the load is not eccentric. By increasing the load eccentricity, the ultimate settlement of the foundation decreases to 30 mm for eccentricity of 0.75 cm and 1.5 cm and 25 mm for eccentricity of 2.25 cm, because by increasing the load eccentricity, less settlement is needed to mobilize soil resistance. Models were pressured to the maximum until 40 mm vertically displacement in order to avoid boundary effects.

$$q' = 0 \Rightarrow q' = \frac{V}{A'} - \frac{My}{I} = 0 \Rightarrow \frac{V}{\pi R^2} = \frac{Ve \times R}{\frac{\pi R^4}{4}} \Rightarrow e = \frac{R}{4} \quad (1)$$

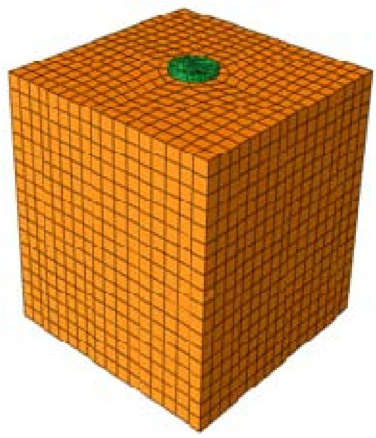

Fig. 2 The geometry of a typical finite element models

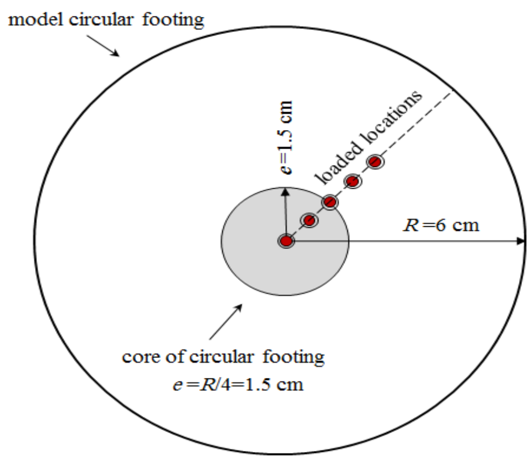

Fig. 3 The core of footing for circular foundation and loaded locations

III. Result and Discussion

Load-settlement curves from models carried out on centrically and eccentrically loaded circular are illustrated in Fig. 4. The ultimate bearing capacity of foundation on soil under centric and eccentric loadings has been obtained from the load-settlement curves according to suggestions made by Boushehrian and Hataf [10] and Sawwaf [9]. In curves with an explicit peak point (Fig. 4 (a)), the ultimate bearing capacity and settlement at failure load are taken at the peak point. Fig. 4 clearly shows the effect of the increasing load eccentricity on the bearing capacity of foundation. The more load eccentricity increase, the more ultimate bearing capacity decreases. Also, by increasing the load eccentricity, the settlement at maximum bearing capacity decreases. In this study, the ultimate bearing capacity was determined at a settlement equal to 18 mm which is s/D=15% (s is the settlement and D is the footing diameter). The ultimate bearing capacity at s/D=15% for centrically loaded was determined 1318 N and for different load eccentricities (e/D=0.625, 0.125, and 0.1875) the ultimate bearing capacity were 1092, 956, and 644 N, respectively.

Two different modes of failure, i.e. general shear failure and local shear failure could be happened for soil layer [23]. In the case of general shear failure, failure surfaces continue to ground surface. In this mode, a slight downward movement of the footing develops plastic points and a sudden failure takes place with a considerable heaving of the ground surface. Thus the load- settlement curve in this mode of failure, has a peak point and the ultimate bearing capacity is well defined (Fig. 4 (a)). In the case of local shear failure, there is a significant compression of the soil under the footing. The local shear failure is characterized by the occurrence of relatively large settlements, slight heaving in surfaces and the fact that the ultimate bearing capacity is not clearly defined. Regarding the load-settlement curves from numerical modeling, it is found that the local shear failure is the mode of failure for centrically loaded footing.

From the results, by increasing the load eccentricity, the mode of failure remains constant (local shear failure), whereas for the case of without eccentricity, the mode of failure changes to general shear failure. For the models with load eccentricity outside the footing core, the failure modes are the local shear failure, while for the load eccentricities inside the footing core and on the footing core boundary, it is similar to general shear failure. As it can be concluded in the case of without eccentricity (Fig. 1 (a)), the softening behavior is obvious. Strain softening is referred to as a behavior where the bearing capacity reduces with continuous development of settlement of footing.

The effect of load eccentricity on modulus of subgrade reaction for different settlement ratios from s/D=5% to s/D=20% are shown in Fig. 5. The modulus of subgrade reaction is a conceptual relationship between contact pressure and footing deflection that is widely used in structural analysis of foundation members [22]. This ratio was defined as (2):

$$k_s = \frac{q}{s} \tag{2}$$

where q is the bearing capacity pressure and s is the settlement of footing. From Fig. 5, it can be concluded that by increasing the load eccentricity, the modulus of subgrade reaction decreases, and for eccentricity more than the footing core, the modulus of subgrade reaction has a greater reduction in comparison with inside the footing core. An increase in load eccentricity and footing settlement leads to a decrease in soil subgrade reaction. Also, in Fig. 6, the modulus of subgrade reaction versus the footing settlement is shown. This plot shows that by increasing settlement, the modulus of subgrade reaction reduces for all of the load eccentricity values and the decrease rate of Ks proportional to settlement increase, reduces. Thus by increasing the load eccentricity form centric loading (e/D=0) to e/D=0.1875, the modulus of subgrade reaction has reduced approximately 60% for settlement rate of s/D=5% and almost 45% for s/D=20%.

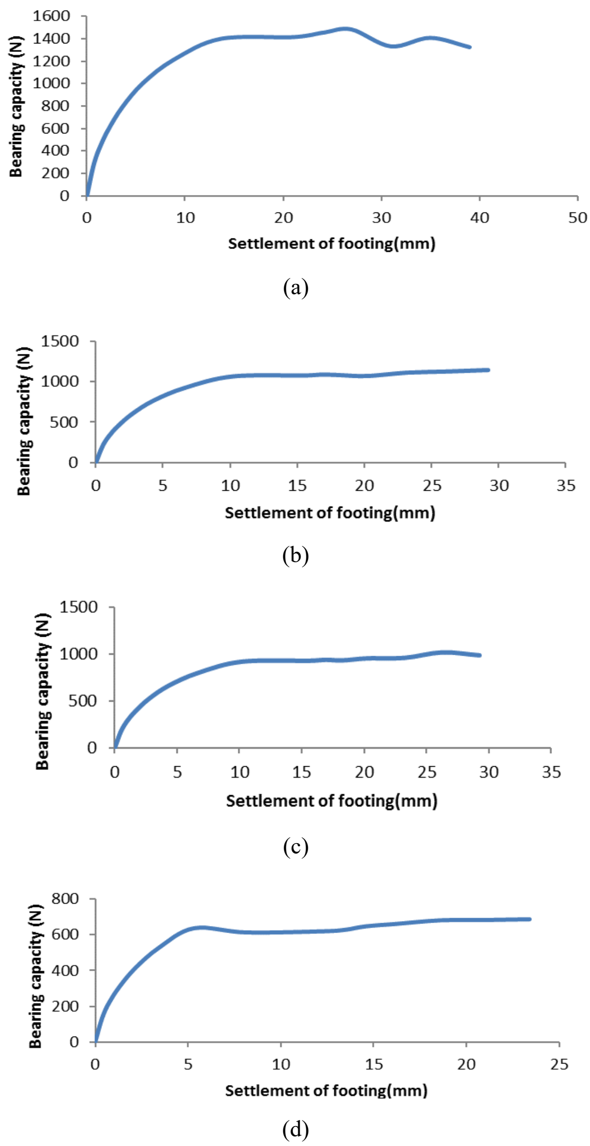

Fig. 4 Load-settlement curves for various load eccentricity: (a) e= 0 (b) e= 0.75 cm (c) e=1.5 cm (d) e= 2.25

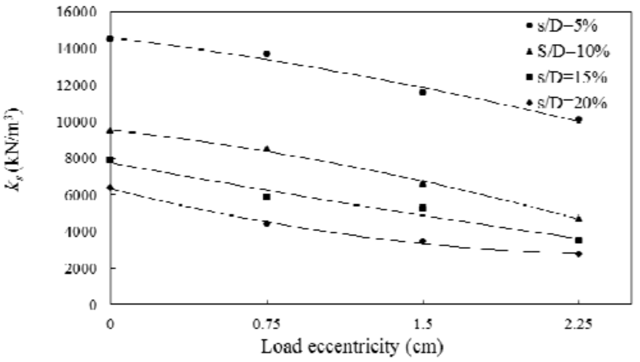

Fig. 5 Modulus of subgrade reaction versus the load eccentricity

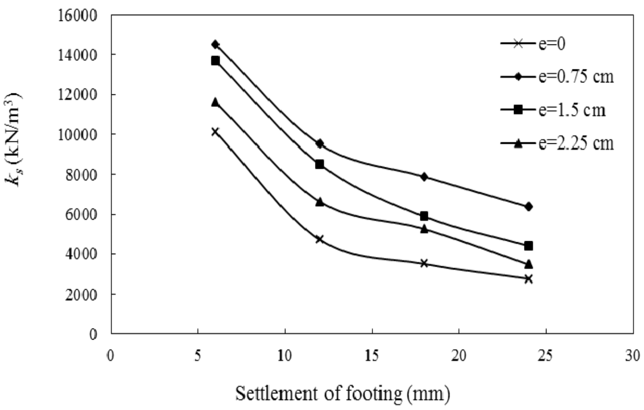

Fig. 6 Effect of footing settlement on modulus of subgrade reaction

IV. Conclusion

This paper presents the data obtained from numerical modeling carried out on the shallow circular foundation model with 12 cm diameter under eccentric loading resting on the sand. Based on the results, the following main conclusions are drawn:

- By increasing the load eccentricity, ultimate bearing capacity decreases and this reduction is larger when the load eccentricity is bigger than footing core (R/4). The one of the reason in reduction of bearing capacity is footing tilt in eccentrically loading. In addition, in load eccentricity of 2.25 cm, the maximum footing tilt is happened. Thus, there is a direct correlation between load eccentricity and footing tilt.
- Calculating the modulus of subgrade reaction (ks) shows that by settlement increasing, this modulus decreases. Also, by increasing the load eccentricity the modulus of subgrade reaction decreases; however, the rate of decrease becomes lower by increasing the settlement.
- The result of this research shows that Druger-Prager model and finite element analysis have good capability of modeling the behaviour of footing resting on sand. This constitutive modeling represented the failure mechanism well.
- The failure mechanism for sand in centrically loaded circular footing is local shear failure, while by decreasing the load eccentricity, it tends to approach general shear failure, and in the case of without eccentricity load, this failure mechanism (general shear failure) is obvious.

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