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Effect of Footing Shape on Bearing Capacity and Settlement of Closely Spaced Footings on Sandy Soil

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***Abstract*—**The bearing capacity of closely spaced shallow footings alters with their spacing and the shape of footing. In this study, the bearing capacity and settlement of two adjacent footings constructed on a sand layer are investigated. The effect of different footing shapes including square, circular, ring and strip on sandy soil is captured in the calculations. The investigations are carried out numerically using PLAXIS-3D software and analytically employing conventional settlement equations. For this purpose, foundations are modelled in the program with practical dimensions and various spacing ratios ranging from 1 to 5. The spacing ratio is defined as the centre-to-centre distance to the width of foundations (S/B). Overall, 24 models are analyzed; and the results are compared and discussed in detail. It can be concluded that the presence of adjacent foundation leads to the reduction in bearing capacity for round shape footings while it can increase the bearing capacity of rectangular footings in some specific distances.

***Keywords*—**Bearing capacity, finite element analysis, loose sand, settlement equations, shallow foundation.

I. Introduction

FOUNDATION construction is one of the basic activities in the field of geotechnical engineering. This issue has provided engineers with efficient analytical and numerical methods for designing various types of foundations over the years. However, some factors such as the heterogeneity of the nature-provided context, non-linear behaviour of earth's materials, and the operational aspects of foundation construction, make each foundation a new challenge and unique experience in projects. In this study, an attempt is made to compare the ultimate bearing capacity and settlement of different foundation types either as an isolated or adjacent to another counterpart circular, square, strip, or ring footing founded on sandy soil with different friction angles (φ). The advanced features of PLAXIS 3D program are applied to create the required load –displacement diagrams. The results are compared with the existing conventional methods.

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II. Previous Studies

The behaviour of circular foundation considering the load-settlement diagram using 3D finite element method investigated by Hashemi and Mohammadi [1]. Keshavarz and Salehi studied the ultimate bearing capacity of strip foundations on two clay layers using two-dimensional finite element method [2]. Ali Elahi and Saber conducted parametric studies on the effect of various forms of ring foundations on bearing and sedimentation capacity [3]. Hosseini and Salehi evaluated the loading behaviour of strip foundation on geogrid reinforced soil layer [4]. The purpose of Anvari and Lotf Elahi Yaghin's study was to investigate the effect of foundation dimensions on its settlement in clay soils [5]. Kumar and Ghosh studied the bearing capacity factor of N_γ for the ring and circular foundations [6]. They consider smooth and rough foundations and calculated the bearing capacity factor using the method of characteristics (MOC). Karaulov performed a series of theoretical and experimental studies on bearing capacity of ring foundations [7]. Loukidis and Salgado examined the bearing capacity of strip and circular foundations on sandy soils [8]. Azam and Naser determined the ultimate bearing capacity of sand reinforced and unreinforced shell foundations using laboratory model test [9]. Cicek et al. indicated the results of laboratory modelling of a surface strip foundation on reinforced and unreinforced sand layer to show the reinforces length effects [10]. They used several foundations considering B values of 1, 2, 3, 5, and 7 as the width in their experiments. Hataf and Shafaghat investigated the behaviour of foundations using PLAXIS 3D. They calculated and compared the bearing capacity of tapered and cylindrical pile foundations using the load-displacement methods. The pile foundation modelling in their study has been conducted using 3D finite element software, which is used in this study [11], [12]. Taiebat and Carter performed numerical studies on the bearing capacity of shallow foundations on cohesive soil subjected to combine loading [13].

III. Methodology

A. The 3D Finite Element Software

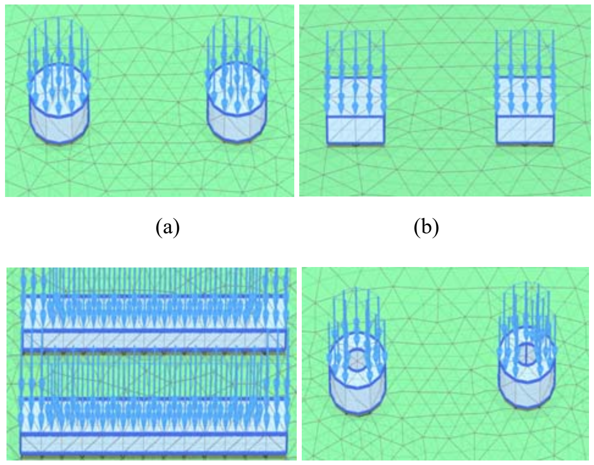
PLAXIS 3D is a finite element program that has been developed specifically to analyze the transformation and sustainability of geotechnical engineering projects. The process of graphically importing data makes the possibility that the complex samples of finite element can be produced and analyzed easily in the minimum time. Conducting the calculation is automatic and based on powerful finite element method. Actually, in PLAXIS, it is possible to model complex geotechnical problems such as soil and structure interaction [14]. In the software, the Mohr-Coulomb behaviour model, the hyperbolic model, the hardening soil model, softening model, and Cam-Clay can be applicable. Moreover, this software can model the process of building and drilling by enabling and disabling the elements in the computation stage. Soil in nature is rarely classical (all isotropic and elastic). In fact, landslides, liquefaction, leaks, and problematic layers, etc. may cause problems for building construction. PLAXIS 3D is a finite element package considered for analysis of soil and foundation deformations and sustainability in geotechnical engineering and it possesses some features to calculate and deal with various aspects of complex geotechnical structures and construction procedures. In the finite element method, the Earth is essentially a continuous model and discontinuities can be modelled separately. Program environment is divided into a limited number of elements connected at node points. Each element is finite, i.e. it has specific geometry and a limited size. Earth stress-strain relation is expressed as an appropriate behavioural rule. Stress, strain, and deformation are caused by changes in ground conditions. The formed stress, strain, and deformation in an element affect the behaviour of its adjacent elements. Complex relations between connected elements create a very complicated mathematical problem. Equation system that relates unknown values to known ones is expressed in terms of a stiffness matrix. In addition, the basic components of the structural objects can be assigned to the geometric model for simulating the tunnel cover and the walls. After the components of the geometric model are created, some dataset should be imported for modelling the materials depending on the behavioural model chosen for the analysis of the finite element in the software.

B. Dimensions of the Numerical Modelling

In order to take the dimensions of the numerical model into account, conditions must be provided so that the foundations represent a behaviour similar to the case when they are on the ground. Therefore, minimum dimensions should be considered so that the development of stress zones under the foundations and around them could actually exist. In order to avoid the direct effect of the boundaries on analysis, appropriate dimensions should be taken for the model. Soil cluster dimensions should be included in the height of 2.5L and the width of 2.5L (1- ν) [15]. In this study, to make the calculations more precise, cluster dimensions are considered as the height of 16 m and the width of 30 m. In this study, the dimensions of square foundation are 2mx2m, the diameter of circular foundation equals 2 m, the width of strip foundation is 2 m and the length is 20 m, and the inner and the outer diameter of ring foundation are 0.8 m and 2 m, respectively.

C. Numerical Modelling

For modelling in this program, initially, soil model or cluster should be constructed in a specified dimension. After creating the soil cluster, the status of underground water should be specified, and some characteristics of a soil are attributed to this cluster as well. In Fig. 1, an overview of geometry, meshing, and loading of foundations are shown.



(a) (b) (c) (d)

Fig. 1 Geometry, meshing and loading of the (a) Circular foundation model for S/D=3, D=2m. (b) Square foundation model for S/D=3, B=2m. (c) Strip foundation model for S/D=3, B=2m, L=20 m. (d) Ring foundation model for S/D=3, Dout=2 m, Dint=0.8 m

Furthermore, the properties of used sand and footing material are presented in Tables I and II, respectively.

TABLE I
PROPERTIES OF USED SAND IN MODELLINGS

Properties	Values
Model	Mohr-Coulomb
$\gamma\ (kN/m^3)$	17
ϕ(degrees)	25°
ψ(degrees)	0
E(MPa)	20
υ	0.2
C(kPa)	0.01
R_{Inter}	0.7

TABLE II
PROPERTIES OF FOOTING MATERIAL IN MODELLINGS

Properties	Values
Material	Concrete
$\gamma\ (kN/m^3)$	27
Drainage	Non-porous
Model	Linear Elastic
E(MPa)	$20*10^3$
υ	0.1

To evaluate the results, the dimensionless parameter (If) is used. In order to measure the bearing capacity of an interfering foundation, the coefficient of interference (If) is defined as:

$$I_f = \frac{q_u(int.)}{q_u(single)} \tag{1}$$

where, $q_u(int.)$ is the ultimate bearing capacity of adjacent foundations, and $q_u(single)$ is the ultimate bearing capacity of an isolated foundation with the same dimension. The bearing capacity of each footing is obtained through load – settlement diagram considering a specific settlement for all of the footings through analytical method. The relations considered for estimating the settlement of rectangular and circular footings are as (2) and (3). Therefore, by finding the approximate settlement of the footings, using the load-displacement diagram, the bearing capacity of each footing is obtained.

$$S_{av} = \frac{qB(1-\vartheta^2)}{E}\mu_0\mu_1 \quad (2)$$

$$S_{av} = \frac{qR}{E}\eta_0\eta_1 \quad (3)$$

In the above equations, μ_0, μ_1, η_0, and η_1 are influence factors which can be obtained from different charts. For a rectangular footing, B is the width, L is the length and q is the applied pressure on the footing. For the circular footing, R is the radius of the footing and E and ϑ are Young's modulus and Poisson's ratio of the soil, respectively. These solutions are based on the theory of elasticity exist only for simple geometries of footings and a layer of homogeneous soil extended H below the foundation to an incompressible layer.

IV. Results and Discussion

This section includes investigating the effect of adjacent foundations' geometry on the bearing capacity and settlement and comparing with the similar state of an isolated foundation. The data of bearing capacity and the settlement of each isolated and adjacent foundation are compared and then the load-settlement diagrams of each model are compared to each other.

A. Effect of Foundation Geometry

In this study, the results are evaluated and compared in loose sandy soil. In sandy soil, the focus is on the internal friction angle of the soil, which is considered 25°. The diagrams of load-settlement for each of the numerical analyses in circular, square, strip and ring foundations as average normalized curves are indicated in Fig. 2.

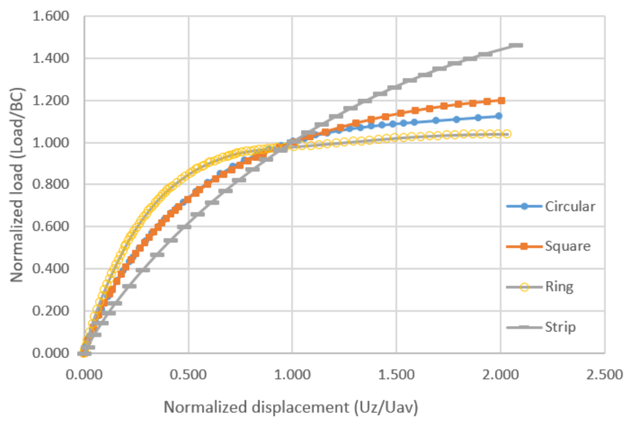


Fig. 2 Normalized load-settlement diagrams for each of the footings

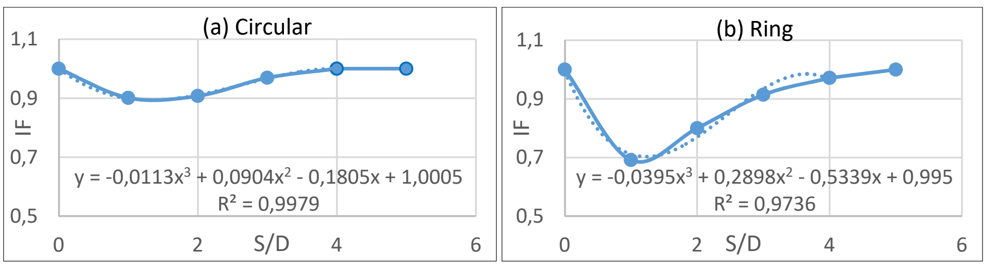


Fig. 3 The diagram of variations of the interference coefficient with distance ratio for (a) Circular foundation (b) Ring foundation

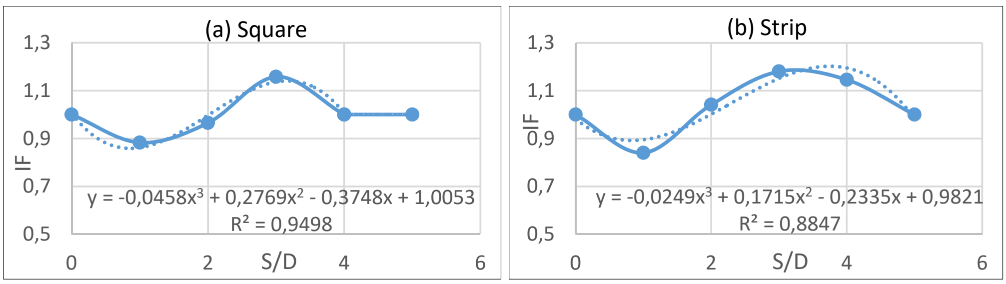
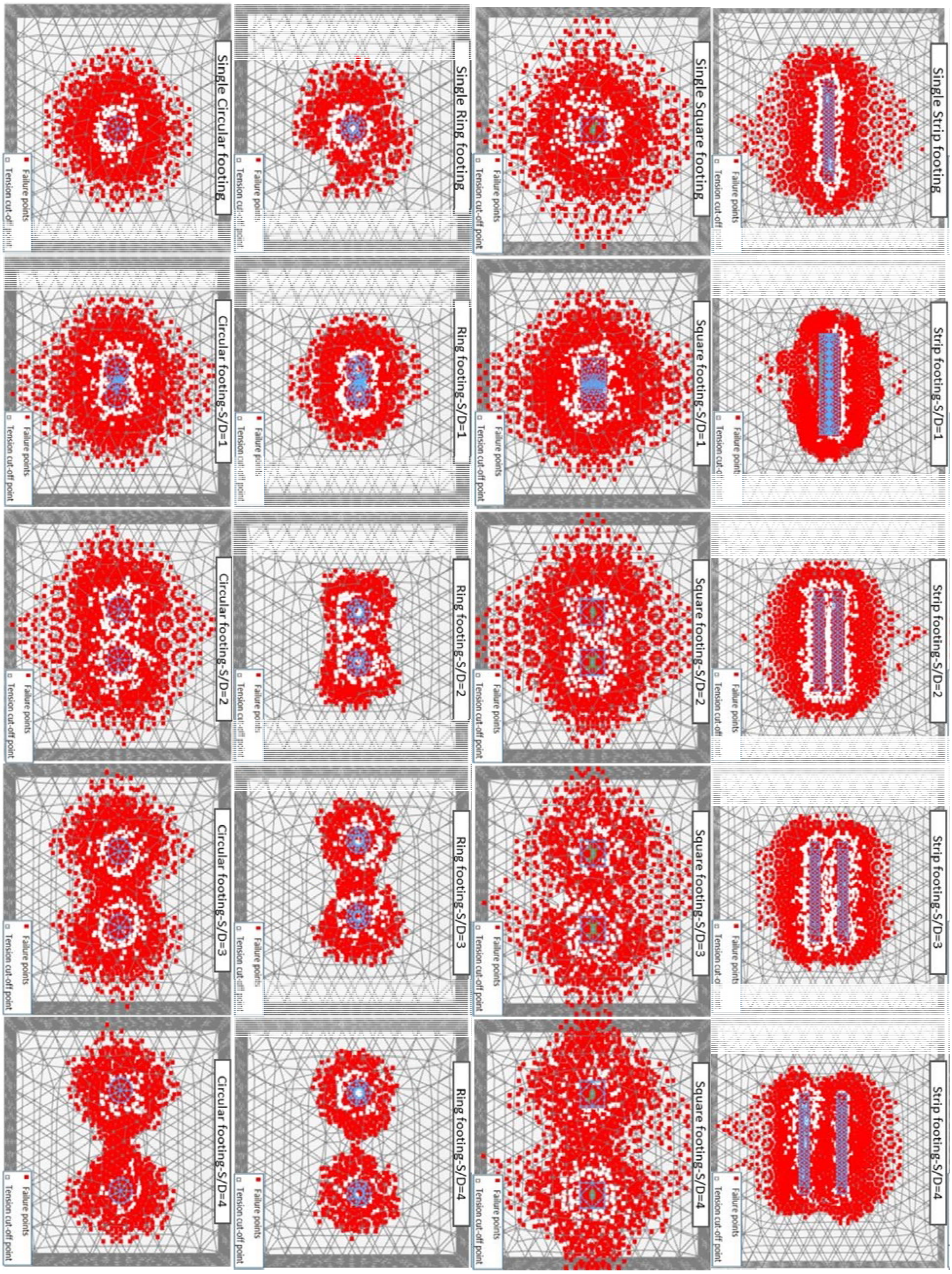


Fig. 4 The diagram of variations of the interference coefficient with distance ratio for (a) square foundation (b) strip foundation



(a) (b) (c) (d)

Fig. 5 Plan view of distribution of plastic points based on Mohr Coulomb surrounding the footings as isolated (at top) and S/D ratios of 1 to 4
(a) Circular footing (b) Ring footing (c) Square footing (d) Strip footing

B. Effect of Foundation Geometry on the Bearing Capacity and Settlement

As it can be observed, by increasing the spacing, the bearing capacity of circular and ring footings decreases until the spacing reaches four times of footing diameter which they act as an isolated foundation. The diagram of the influence factor for different distances of footings for circular and ring geometries in loose sand are presented in Fig. 3. The maximum influence factor, (If), which represents the lowest bearing capacities in circular and ring footings is related to spacing to diameter ratio of 1 to 1.5 (S/D=1 to 1.5). The value of S/D=0 resembles an isolated footing condition.

Fig. 4 is presenting the interference factor versus different spacing ratios for square and strip foundations. Figures suggest that for rectangular footings the interference factor decreases at first and then it experiences an increasing trend until it reaches to value of 1, which is a situation that footings behave similarly to isolated ones. The lowest and the uppermost If for the square footing occur for approximate S/D ratios of 0.7 and 3 respectively. These values for the strip footing occur at S/D of 1 and 3.2, respectively. For the rectangular footings, D is considered as the width of the footings.

C. Plastic Points

In order to have a broader perspective into the behaviour of footings, the plan view of plastic points surrounding them for all of the geometries are plotted. Fig. 5 illustrates the distribution of plastic points according to the Mohr Coulomb failure criterion surrounding footings. The left column of figure is related to circular footing from top as isolated one to the bottom as with presence of adjacent footing with S/D= 4. This pattern repeats for ring, square, and strip footings from left respectively. Figures suggest that circular and square shaped footings affecting the surrounding soil wider and make more plastic points adjacent to them. However, for ring and strip footings the distribution of plastic points in surrounding soil is much closer and confined. The red marks are representing plastic points based on Mohr Coulomb criterion and the white signs are representing tension cut-off points.

V. Conclusions

The following conclusions can be drawn from the results of this study. When centre-to-centre distance ratio between foundations is greater than 4 (S/D=4), adjacent foundations no longer affect each other, and they can be treated as isolated foundations. Among circular and ring foundations, the maximum obtained values of If are 0.89 for S/D=1.2 and 0.7 for S/D=1 respectively. These values for rectangular footings (as square and strip geometries) reach to 1.15 for S/D=3 and 1.2 for S/D=3.1, respectively. This indicates the reduction in bearing capacity for round shape footings compared to when they act isolated. However, for rectangular footings increasing in bearing capacity can be concluded in S/D ratios 2.5 to 3.5.

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