Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
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doi: 10.3850/GRF-25280825_isgsr-048-P166-cd

EFFECT OF EMBEDMENT DEPTH ON BEARING CAPACITY OF STRIP FOOTING PLACED OVERA SPATIALLY VARYING c-ϕ SOIL WITH NON-STATIONARY CHARACTERISTICS

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The realistic soil strength profiles have spatially varying soil properties as well as varying mean and standard deviation of soil parameters along with the increasing depth. This soil profile with varying soil properties along the depth is modelled using a non-stationary random field. The consideration of spatial variability in soil affects the bearing capacity and failure mechanism and thus plays a vital role in the design of shallow foundations. Studies have explored the bearing capacity of surface strip footings on clayey soil with spatially varying strength properties. However, limited work is available on embedded footing and sandy soil. Hence, this paper aims to study the effects of embedment depth of strip footing placed on a spatially varying c-ϕ soil with increasing mean strength values along the depth. The probabilistic analysis is carried out to investigate the bearing capacity with upper bound limit analysis using finite element-based software OPTUM G2 via MATLAB interface. The study covers a comparison of results of non-stationary random fields produced with different strength gradients, and also the statistical characteristics of the resulting bearing capacity are evaluated. A detailed discussion on the effects of vertical correlation length, strength gradient and different coefficient of variations (COVs) is mentioned in the paper. The difference in results due to stationary and non-stationary random fields are also explored.

Keywords: Spatial variability, Non-stationary random field, Probabilistic analysis, Strength gradient, Bearing capacity, Scale of fluctuation.

1. Introduction

Bearing capacity evaluation is an important step in foundation design. The soil properties have a great influence on the bearing capacity evaluation. For many decades, different analytical and numerical methods have been developed to calculate the bearing capacity of shallow footings. Different methods like the limit equilibrium method (Narita and Yamaguchi 1990), slip-line method (Graham et al. 1988), the limit analysis method (Georgiadis 2010, Leshchinsky and Xie 2017), including upper and lower bound theorems have been developed. Researchers have also studied the bearing capacity of the surface footing as well as embedded footing and have carried out the bearing capacity estimation. Salgado et al. (2004) investigated a series of lower and upper-bound limit analysis of different footings embedded at a depth below the ground surface and observed a significant difference in bearing capacity factor due to the embedment.

The realistic soil domain has the random character of physical and mechanical soil properties, which is not usually considered. The inherent soil variability has been widely recognized as a significant source of uncertainty that affects the bearing capacity of the foundation or any geotechnical structure (Griffiths et a. 2002, Cho and Park 2010, Wu et al. 2019). Studies have been reported about the probabilistic bearing capacity of shallow foundations on clay soil. Very few studies have been conducted on probabilistic bearing capacity on c-ϕ soil (Fenton and Griffiths 2003). The natural soil profiles have varying soil properties, which increase along the depth. This soil profile along the depth is modelled using nonstationary random field. The bearing capacity of strip footing on spatially varying c-ϕ soil considering nonstationary characteristics remains unexplored. The present study investigates these effects through a detailed analysis. Different embedment depths are also assumed to understand their effect on the bearing capacity.

2. Numerical Model Details

The present study examined the stochastic results of an embedded strip footing in a c-ϕ soil subjected to vertical load.

The probabilistic bearing capacity analysis conducted in this study is based on the plane strain element model and the Mohr-Coulomb failure criteria is adopted for the model. A strip footing placed on horizontal ground considering the spatial variability of soil is considered. A random finite limit analysis considering the upper bound is carried out for the evaluation of the bearing capacity in OPTUM G2 software via MATLAB interface.

In the present model, the width (B) of the footing is 2m, and the embedment ratio assumed is 0, 0.25, 0.75 and 1. The dimensions of the soil domain are $40B \times 20B$ as shown in Fig 1. The soil and foundation interface are assumed to be rough. The soil domain is composed of 10,000 elements. The random finite element model incorporates five different parameters: Cohesion (c), friction angle(ϕ), young's modulus(E), Poisson ratio (ν) and dilation angle (ψ). The E, ν, ψ values are held constant and c and ϕ are considered as random variables. The random variables c and ϕ are independent in terms of cross correlation in the OPTUM G2 software. The values of the soil parameters used are mentioned in Table1. The strip footing is modelled as a rigid element with a unit weight of 22 kN/m^3. To evaluate the bearing capacity for increasing soil strength along the depth i.e. nonstationary characteristics (Fig 2.), different strength gradients (M) are considered. The typical values of strength gradient vary between 0-3.5 kN/m^3 (Ke et al. 2021). Hence the study uses a range of strength gradient values (Table 1.) to understand its effect on the bearing capacity. The convergence graph of mean bearing capacity of the strip footing for coefficient of variation (COV) = 0.2, horizontal correlation length (l_x) = 4m, vertical correlation length (l_y) = 1m is shown in Fig 3.

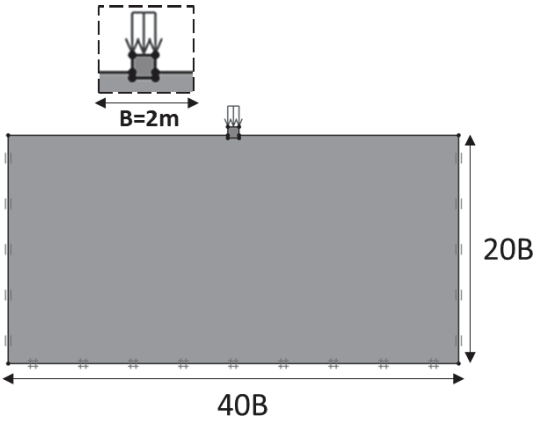

Fig 1. Schematic diagram of the numerical model

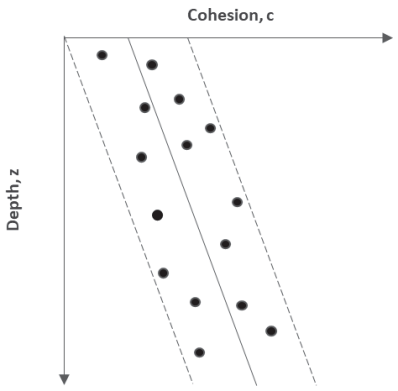

Fig 2. Representation of increasing cohesion along the depth

Table 1. Soil parameters used in the study

Parameters	Values
Material type	Mohr-Coulomb
Cohesion, c (kPa)	5
Friction angle, ϕ (°)	35
Unit weight, γ (kN/m^2)	20
Young modulus, K(MPa)	25
Coefficient of variation	0.1, 0.2, 0.3
Vertical correlation length (m)	0.5, 1, 5
Horizontal correlation length (m)	10
Strength gradient, M (kPa/m)	0.25, 0.5, 0.75, 1.3

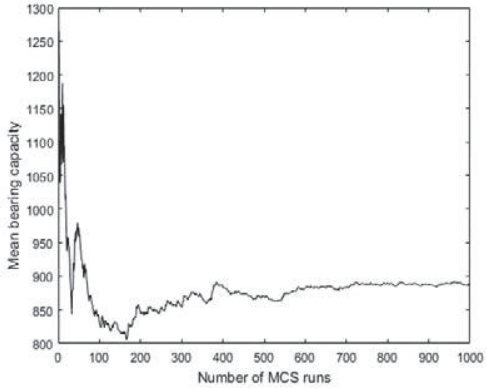

Fig 3. Convergence graph of mean bearing capacity of strip footing for COV=0.2, l_x = 4m, l_y = 1m

3. Results and Discussion

This section describes the parametric study on the influence of spatial variability, nonstationary characteristics and embedment depth ratios on the bearing capacity of strip footing. The study conducted is first validated with some previously reported literature on the bearing capacity of strip footing on sandy soil, as shown in Fig 4.

It can be observed that the ratio of bearing capacity for footing at depth D to that obtained for surface footing denoted as (d_γ) is comparable to the literature reported. An upper bound limit analysis has been conducted to evaluate the probabilistic bearing capacity considering different strength gradients for the c-ϕ soil. Fig 5. displays a diagram of a nonstationary random field with strength gradient M=0.5, COV=0.2, l_y =1m, and l_x= 10m.

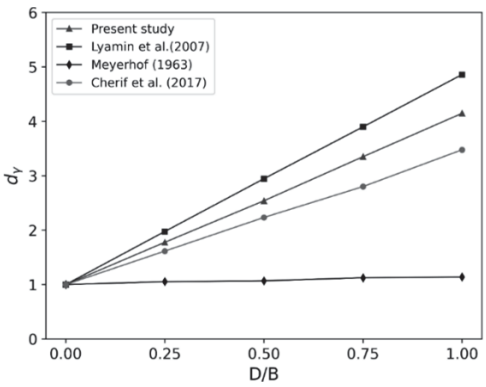

Fig 4. Validation of present study with reported literature

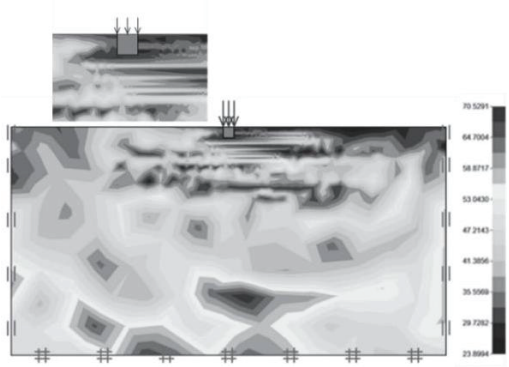

Fig 5. A nonstationary random field with strength gradient M=0.5, COV=0.2, l_y =1m, l_x= 10m

3.1. *Effect of correlation length*

This section elucidates the influence of vertical correlation length on the normalized bearing capacity of footing on c-ϕ soil. The correlation lengths and coefficient of variation employed is l_y =0.5m, 1m, 5m, l_x =10m and 0.2 respectively. The embedment depth used in this study is equal to the width of the footing.Fig 6. (a). shows the cumulative density function plot of bearing capacity for different correlation lengths. The cumulative distribution of l_y =0.5m and l_x= 10m is widespread as compared to other two cases. This shows that the distribution has wide dispersion in the bearing capacity values.

3.2. Effect of coefficient of variation

Fig 6. (b). represents the CDF curves for different coefficient of variations. The variability parameters considered for this are l_y=1m, l_x= 10mand COV= 0.1, 0.2, 0.3. Considered embedment depth ratio (D/B) is 1. It is observed that with increasing COV values, the CDF curve shifts towards the left. Hence it can be reported that with increase in COV (higher randomness) the bearing capacity decreases. The possible reason is the increasing variability due to increasing COV.

3.3 Effect of strength gradients

This section describes the effect of different strength gradients on the bearing capacity and compares the case of stationary and nonstationary characteristics. The depth of the footing is the same as the width of the footing. The other parameters considered for this case are l_y =1m, l_x =10m and COV= 0.2. From Fig 6. (c), it can be clearly observed that the difference between CDF curve for embedded footing for stationary cases and nonstationary cases with different strength gradients. The greater the strength gradient value, and the greater the CDF curve towards the higher bearing capacity values. The stationary case experiences low bearing capacity as compared to all cases with strength gradients greater than zero.

3.4. Effect of embedment depth

This part of the study considers set of different embedment depths to understand their effect on the bearing capacity. The correlation lengths and coefficient of variation considered are l_y=1m, l_x= 10m and COV= 0.2. The strength gradient used is 0.5. It can be clearly noted that when the footing was placed at the surface, a smaller bearing capacity value was obtained. The CDF curves mentioned in Fig 6. (d), concludes that with the increase in the embedment of footing, the plot shifts towards the increasing bearing capacity values. Due to

increasing embedment depth, confined mechanism is developed and thus bearing capacity increases. A clear difference in the distribution of footing at surface (D/B=0) and D/B=1 is noteworthy in this study.

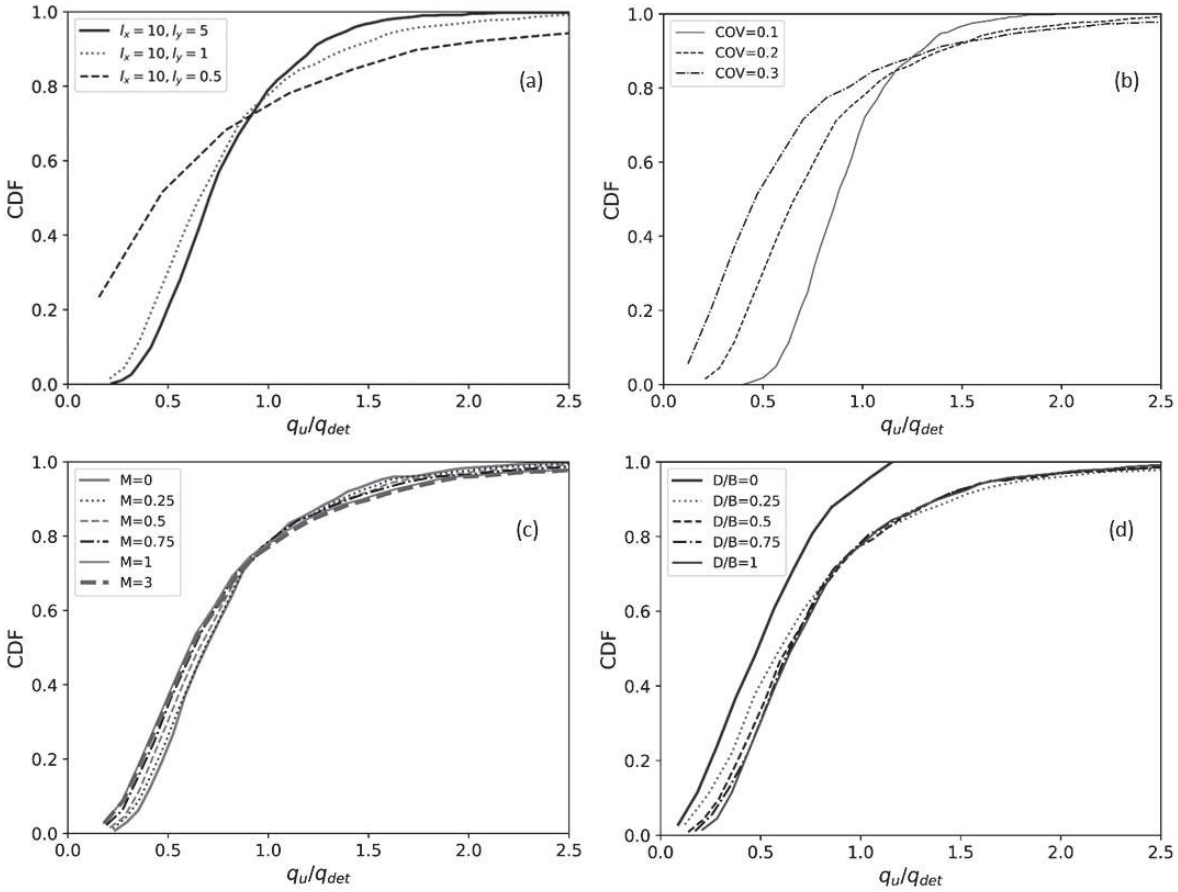

Fig 6 (a). Cumulative density function plot of bearing capacity for different vertical correlation lengths. Fig 6 (b). Cumulative density function plot of bearing capacity for different coefficient of variation. Fig 6 (c). Cumulative density function plot of bearing capacity for different strength gradients. Fig 6 (d). Cumulative density function plot of bearing capacity for different embedment depths

4. Conclusions:

A study for different embedment depths of strip footing on c-ϕ soil was conducted with the consideration of the nonstationary characteristics. The following conclusions were drawn from the analysis carried out:

- There is a clear difference in the normalized bearing capacity because of different vertical correlation lengths.
- The higher value of coefficient of variation for c and ϕ shows lower value of normalized bearing capacity indicating that due to a higher spatially variable soil, the bearing capacity of embedded strip footing is poor
- A significant difference in the normalized bearing capacity for stationary and nonstationary case can be observed for the embedded footing. The nonstationary case has greater mean bearing capacity value. The embedment depth also has great impact on the bearing capacity. For any nonstationary case, greater embedment depth gives higher bearing capacity.

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