International Journal of Environmental Sciences
ISSN: 2229-359
Vol. 11 No.4,2025
https://theaspd.com/index.php

Stress-Settlement Response of Circular Foundation on Granular Layer Overlaying Compressible Normally Consolidated Soil

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Abstract. *Bearing capacity of foundations is typically estimated by assuming the soil strata to be homogeneous and rigid plastic. However, for footings on compressible strata is influenced not only by the strength parameters but also by the settlement of the soils beneath the foundation. Stress-settlement behavior of footings on soft ground is inherently nonlinear due to compressibility nature of the soil. Naturally sedimented soils undergo variations in undrained shear strength with depth. Compressibility and heterogeneity of normally consolidated (NC) soil influence the bearing stress as a function of settlement. The current study considers circular footing resting on granular bed overlaying compressible normally consolidated soil (GNC). The numerical study quantifies the effects of NC soil's heterogeneity and compressibility, as well as granular layer thickness on stress-settlement responses of footings on GNC soils. Results of the present study depict that bearing stress increases with rigidity and heterogeneity in NC soil as well as the with the thickness of granular layer. The increments in stress with granular layer thickness and NC soil heterogeneity increase with footing settlement, whereas they decrease with the rigidity of NC soil. The influence of granular layer thickness on bearing stress is more significant for given footing settlement when compared to that due to heterogeneity and rigidity of NC soil.*
Keywords: *Compressibility, Granular layer, Heterogeneity, Numerical analysis, Undrained Shear strength.*

INTRODUCTION

Axisymmetric structures such as silos and storage tanks are founded on circular footings. The stability and performance of structures are significantly influenced by the bearing capacity of foundations, which is often estimated under the assumption of incompressible and homogeneous soil with depth. However, many construction sites have heterogeneous, layered or stratified and compressible soils. These stratified soil profiles often consist of different materials or have varying engineering properties such as strength, compressibility, etc. Soft soil deposits are characterised by low shear strength, c, and high compressibility. Shear modulus of clays, G, influences the bearing stress as a function of settlement. Based on Duncan and Buchignani's [1] field observations, shear modulus is about 50-500 times that of undrained strength. Vesic [2] proposed compressibility factors as a function of rigidity index, I_r (=G/c), for computing the ultimate bearing capacity of foundations using cavity expansion theory. For a young naturally sedimented deposit, undrained strength increases linearly with depth [3]. The influence of soil heterogeneity on bearing capacity of footing has been analysed by several researchers based on plasticity theory [4, 5] and numerical analysis [6, 7]. It is observed that soil's heterogeneity with depth increases the bearing capacity of footings. Shiva Bhushan et al [7] studied the influence of compressibility on bearing capacity of circular embedded foundations accounting for heterogeneity. The granular strata laid over compressible normally consolidated soils improves the bearing capacity and settlement response of footing. This layer also provides a good platform to distribute the load from foundations over a wider area. Hanna and Meyerhof [8] proposed bearing capacity charts for sand overlying soft soil, considering punching mechanism [9]. Bearing capacity charts for sand over clay are proposed for circular footing based on centrifuge test results [10, 11]. The effect of soil heterogeneity and footing roughness on bearing capacity of circular footing on sand overlying clay is studied by Shiau et al. [12]. The optimum thickness of granular layer varies with undrained strength of clays [13], with the failure pattern of sand indicating wide spread of plastic zone. Biswas and Murali Krishna [14] experimentally studied the stress–settlement responses of circular foundation resting on sand overlying clay.The current study investigates the influence of compressibility and heterogeneity in NC soils on stress-settlement response of circular footing on granular layer overlying normally consolidated soil. The effect of granular layer thickness on stress-settlement behavior of circular footing is also studied.

Problem Statement

A circular footing of 5 m dia, *D*, resting on granular bed overlying normally consolidated (GNC) soil is analysed (Fig. 1). Normally consolidated (NC) ground is a compressible soil whose undrained strength increases from its surface value, c_0, linearly at a rate of ρ with depth. The undrained strength of soil at any depth, z, equals $c_0+\rho z$.

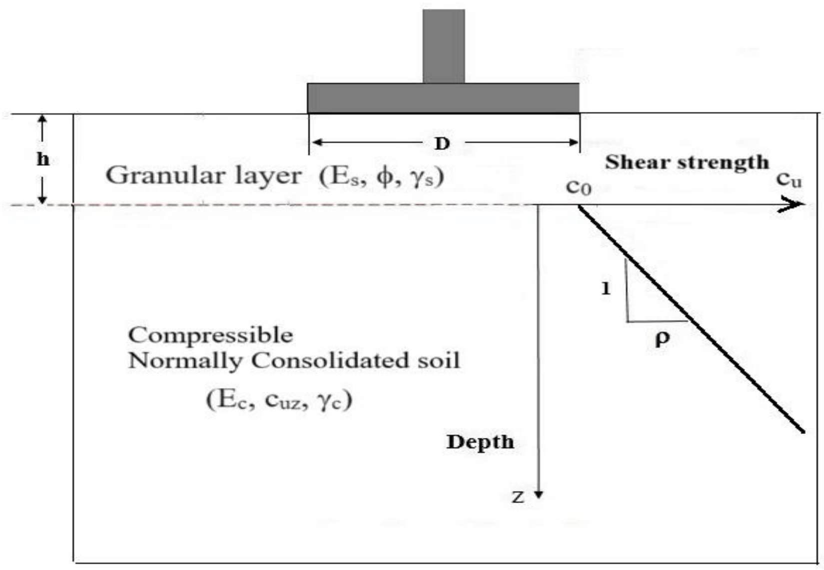


Fig. 1. Definition sketch of footing on granular layer over compressible NC ground

Table 1. Properties of layered soil

Property	Value
Undrained strength at ground level, c_0	10 kPa
Angle of shearing resistance of granular layer, ϕ	35^0
Deformation modulus of sand, E_s	20 MPa
Deformation modulus of clay, E_c	1500, 2000, 3000 and 6000 kPa
Thickness of granular layer, h	1.0, 1.5, 2.0 and 2.5 m
Rate of increase, ρ, of undrained strength with depth	0, 1, 2 and 5 kPa/m

Properties of soils considered are presented in Table 1. Unit weight, γ_c, and Poisson's ratio of NC soil are 15 kN/m^3 and 0.499, respectively. Deformation modulus, E_s, and unit weight of granular strata, γ_s, are 20 MPa and 19 kN/m^3, respectively. The angle of shearing resistance, ϕ, and Poisson's ratio of granular soil are 35° and 0.30. The rate of increase in undrained strength with depth, ρ, is varied from 0 through 5 kPa/m. The deformation modulus of NC soil, E_c, is varied from 1500 kPa to 6000 kPa. The granular layer thickness, h, is varied from 1.0 m to 2.5 m.

METHODOLOGY

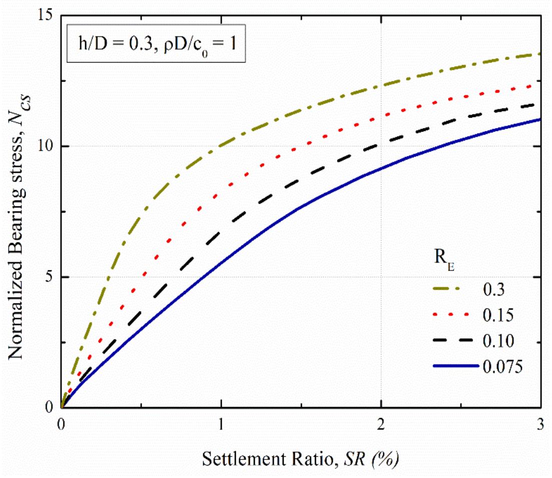
Axisymmetric finite element analysis was carried out using PLAXIS 2D software. Mesh geometry was 15 noded triangular elements. Vertical and lateral boundaries were positioned at six times the diameter of the footing. Lateral boundaries are fixed in radial direction, bottom boundary in both radial and vertical directions while the top boundary is free. An incremental load was applied over half the footing width as the model is symmetric about vertical axis. Footing is modelled as an elastic plate element with normal

stiffness (EA) of 7.6x10^6 kN/m. Mohr-coulomb soil models were used to simulate the sand and clay materials. Numerical analysis evaluates the stress-settlement behavior of circular footings resting on GNC ground, accounting for effects of compressibility, heterogeneity, and granular bed thickness.
The study is limited to a vertical displacement of 15 cm i.e., 3% of footing diameter. Strength and stiffness increase gradually with a rate of ρ and $\rho(E_0/c_0)$ with depth to maintain a constant rigidity index, at any depth in NC soil. Stiffness ratio, R_E, is defined as the ratio of deformation modulus of clay to sand material i.e., $R_E = E_c/E_s$. The range of the parameters considered for the study are as follows: Stiffness ratio, R_E: 0.075 to 0.3. Degree of heterogeneity, $\rho D/c_0$: 0 to 2.5; Granular layer thickness ratio, h/D: 0.2 to 0.5. Bearing stress of GNC soil is obtained as a function of foundation settlement for individual parameters of the study.

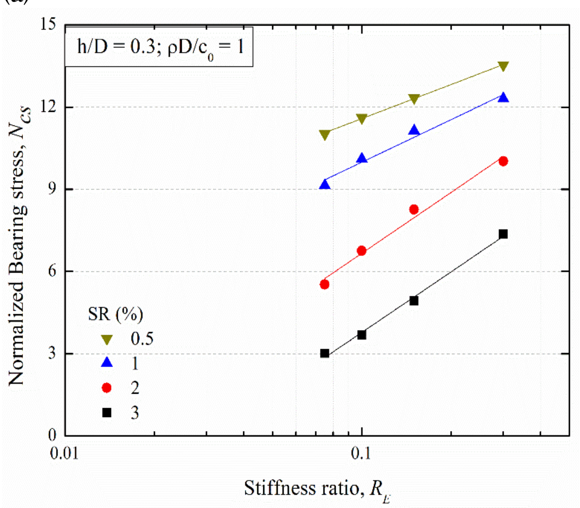
RESULTS AND DISCUSSION

A circular footing of 5 m dia, D, resting on granular bed overlying compressible NC soil is considered for the analysis. The bearing stress for various prescribed settlements is normalized by undrained strength, c_0 as N_{cs} (= q/c_0), and settlement is normalized by footing diameter, D, and is defined as Settlement Ratio, $SR = 100s/D$. A medium-dense granular stratum of 1.5 m thick and unit weight of 19 kN/m^3 is considered on top of NC ground. Unit weight of NC soil is 15 kN/m^3. The cohesion and internal friction angle of granular strata are taken as 1 kPa and 35°, respectively.

Influence of Compressibility



(a)



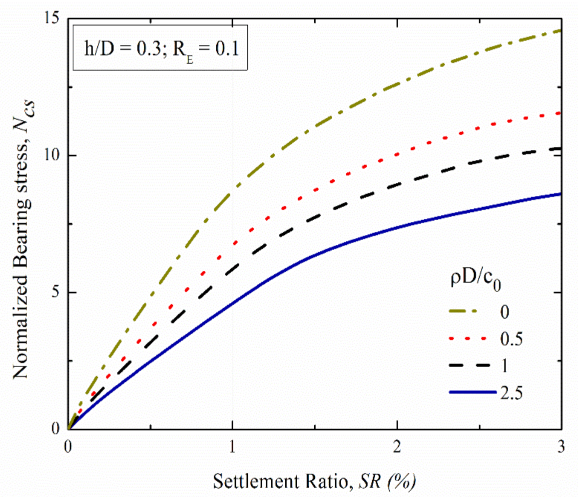
(b)

Fig. 2. Effect of compressibility of NC soil
a) N_{cs} versus SR (%) at different R_E b) N_{cs} versus R_E at different SR.

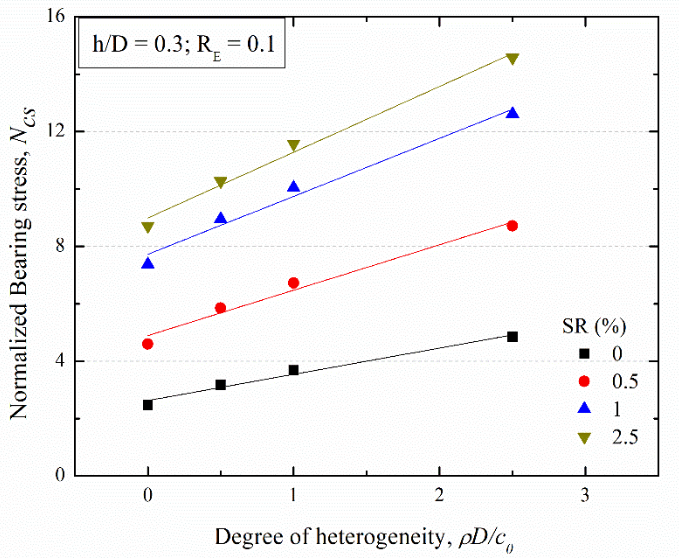
Figure **2(a)** presents the variation of normalized bearing stress with settlement ratio for GNC ground for various deformation modulus of NC soil, for h = 1.5 m. The deformation modulus of clay is varied from 1500 to 6000 kPa, i.e., stiffness ratio, R_E values are taken as 0.075, 0.1, 0.15 and 0.3. GNC possessing relatively a larger stiffness ratio, e.g., 0.3, as expected resulted in higher stresses. N_{cs} increases by 81% for 4-fold increase in the deformation modulus of NC soil, E_c, at SR = 1%. Normalized bearing stress, N_{cs}, is plotted against the stiffness ratio of GNC soil, R_E, on semilog scale for different settlement ratios in Figure **2(b)**. N_{cs} varies linearly with R_E for a given foundation settlement. N_{cs} values increase with R_E significantly at smaller settlements. At SR = 0.5% and 3%, N_{cs} increases by 24.5% and 23%, respectively, for 4-fold increase in deformation modulus from 0.075 to 0.3 of NC layer.

Influence of Heterogeneity in NC soil

Bearing stress-settlement responses of circular footing on GNC ground for varying degrees of heterogeneity, □D/c_0, are studied in this section. Granular layer 1.5 m thick with unit weight of 19 kN/m^3 and angle of shearing resistance of 35° is considered. The deformation modulus of NC layer at its surface, E_0, is 2 MPa. Strength and stiffness increase gradually with rates of ρ and $\rho E_0/c_0$ with depth, respectively, to maintain constant E/c values at any depth. The rate at which undrained strength increase with depth, ρ, in NC layer is varied from 0 through 5 kPa/m, i.e., the degree of heterogeneity, $\rho D/c_0$, varied as 0, 0.5, 1 and 2.5.



(a)



(b)

Fig. 3. Effect of heterogeneity

a) N_{cs} versus SR (%) at different $\rho D/c_0$ b) N_{cp} versus $\rho D/c_0$ at different SR.

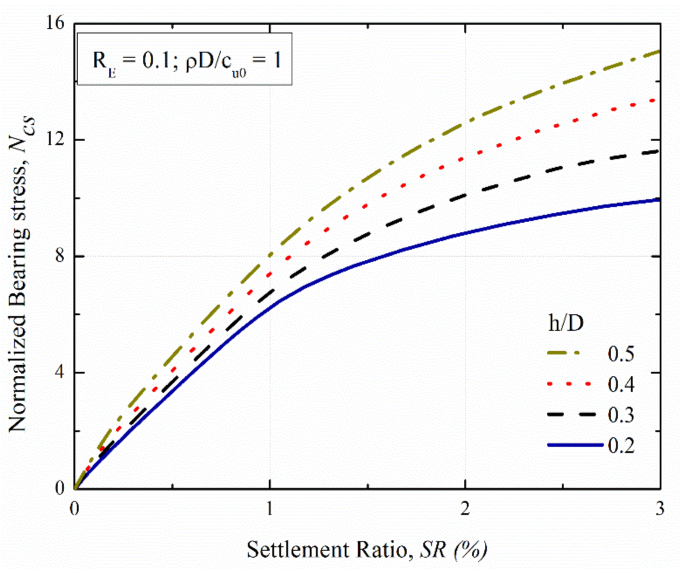
Figure **3(a)** presents the variation of N_{cp} with SR(%) for circular footing on 1.5m thick granular strata overlying compressible NC soil, for various degrees of heterogeneity. GNC ground having a higher degree of heterogeneity in NC layer results in higher bearing stress, due to contribution of layer's undrained strength. N_{cs} increases by 21% for 5-fold increase in $\rho D/c_0$, at SR = 3%. Normalized bearing stress of footing, N_{cs} is plotted against the degree of heterogeneity in NC layer, $\rho D/c_0$, for different settlement ratios and is depicted in Figure **3(b)**. N_{cs} increases linearly with $\rho D/c_0$ for a given foundation settlement. At SR =1% and 2%, N_{cs} increases by 24% and 20%, respectively for 5 times increment in the degree of heterogeneity in NC layer.

Influence of Granular Layer Thickness

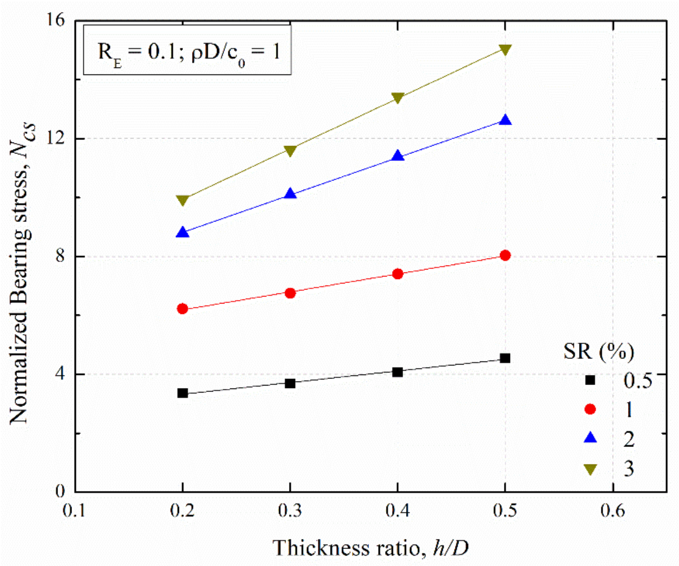
Bearing stress-settlement responses of footing resting on sand of varying thickness overlying NC ground are studied in this section. NC soil has degree of heterogeneity, $\rho D/c_0$, of 1, and stiffness ratio, R_E, of GNC ground is 0.1. Strength and stiffness increase gradually with rates of ρ and $\rho(E_0/c_0)$ with depth to maintain constant E/c value at any depth. The thickness of granular bed, h, is varied from 1.0 m through 2.5 m, and bearing stress versus settlement responses obtained.

Figure **4(a)** presents variations of N_{cs} of footing on granular layer overlying compressible NC with *SR* for different thicknesses, *h/D*, of granular bed. The increment in bearing stress with settlement increases rapidly with thickness ratio, h/D, due to the contribution of granular layer. N_{cs} increases 1.5 times at a settlement of 15 cm for relative thickness, *h/D,* increasing by 2.5 times.

Variations of normalized bearing stress of two-layered soil with the relative thickness, *h/D*, of granular strata for different settlement ratios, SR are shown in Figure **4(b)**. The thickness ratio significantly influences bearing stress values for a given footing settlement, contributing to shearing layer effect offered by granular strata. For *SR* = 1%, N_{cs} value increases from 6.22 to 8.03 for *h/D* increasing by 2.5 times. For *SR* = 0.5% and 3%, N_{cs} increases by 1.35 and 1.51 times, respectively, when the thickness of sand bed increases from 1.0 m to 2.5 m.



(a)



(b)
Fig. 4. Effect of thickness of granular bed
a) N_{cs} versus SR(%) at different h/D b) N_{cs} versus thickness ratio (h/D) at different SR

Figure **5** presents the variation of slopes of N_{cs} on logarithmic scale against settlement ratio, SR(%) for different parameters, *h/D, R_E*, and *ρD/c_0*,. The slope of N_{cs} with *h/D* increases by 4.3 times for 5-fold increase in footing settlement. The increment in bearing stress with settlement increases rapidly with thickness ratio due to large contribution of shear layer effect of granular strata. The slope of N_{cs} with degree of heterogeneity, *ρD/c_0* increases by 2.5 times for 5-fold increase in footing settlement. Slope of N_{cs} with relative stiffness ratio, R_E of GNC ground, reduced by 44% when SR increases from 0.5% to 3%. The slope of N_{cs} with R_E decreases from 7.34 to 4.13 for 5 cm and 15 cm footing settlements, respectively, highlighting the substantial impact of compressibility on bearing stress at smaller settlements, which diminishes with increased settlements.

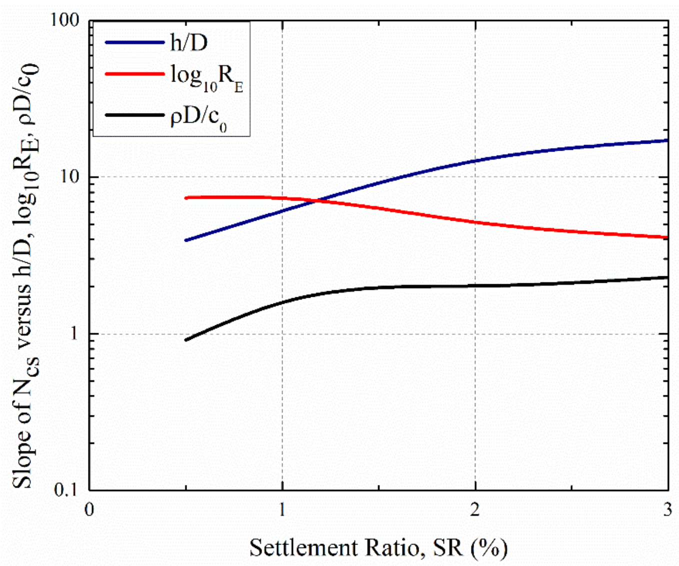


Fig. 5. Variation of slopes of N_{cs} versus different parameters with SR

CONCLUSIONS

Stress-settlement behavior of circular foundations resting on medium-dense granular layer over compressible normally consolidated soil are analysed for different parameters treating the problem as layered soil. Individual effects of compressibility of NC soil, strength variation in the NC layer and granular layer thickness on bearing stress are quantified as function of settlement. Bearing stress of two-layered GNC ground increases with granular layer thickness, stiffness ratio and the degree of heterogeneity parameter in NC layer for a specific settlement. The increments in bearing stress with granular layer thickness and NC soil heterogeneity increase with footing settlement, whereas they decrease with the rigidity of NC soil. The influence of granular layer thickness on bearing stress is more significant for a given foundation settlement compared to that for rigidity and heterogeneity of normally consolidated soil.

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