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Bearing Pressure of Granular Layer Overlying Compressible Normally Consolidated Ground

J. Y. V. Shiva Bhushan[1,2], G. V. Narasimha Reddy[2]
[1]Department of Civil Engineering, VNR Vignana Jyothi Institute of Engineering & Technology, Hyderabad-500090, INDIA.
[2]Department of Civil Engineering, JNT University, Kukatpally, Hyderabad-500085, INDIA.
[1]jyvshivabhushan@gmail.com,[2]gvnreddy@jntuh.ac.in

Abstract. *Bearing capacity of foundations is estimated most commonly considering the soil strata as incompressible and homogeneous. Bearing capacity of footings on compressible strata is governed not only by the strength parameters but also by the settlement of the soils beneath. Load-settlement response is nonlinear for footings resting on soft ground characterized by its compressibility. Naturally sedimented soils undergo variations in undrained strength with depth. Compressibility and heterogeneity of NC soil influence the bearing pressure as a function of settlement. The present study considers footing resting on medium-dense granular bed overlying compressible normally consolidated soil (GNC). The numerical study quantifies the effects of heterogeneity and compressibility of NC soils and granular layer thickness on bearing pressure-settlement response of a circular footing on GNC soils. Results of the present study depict that bearing stress increases with rigidity and heterogeneity in NC soil and granular layer thickness. The increments in bearing pressure 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 pressure 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.*

1 INTRODUCTION

Circular footings provides support for axisymmetrical structures such as storage tanks and silos. Ultimate bearing capacity of foundations, which is frequently estimated under the assumption of incompressible and homogeneous soil with depth, significantly influences the stability and performance of structures. However ground/soil is compressible and the load-settlement response of footings resting on soft ground is non-linear. Numerous construction sites have heterogeneous, compressible and layered soils. These stratified soil profiles often consist of different materials or have engineering properties such as strength and compressibility, that vary with depth. Soft soil deposits exhibits low shear strength, c, high moisture content and high compressibility. Bearing capacity of footings on compressible strata is governed by both the strength and deformation parameters of the soils beneath.

Shear modulus of clays, G, influences the bearing pressure as a function of settlement. Most of the available theories are based on limit state design and do not account for the non-linear stress-strain behaviour of soils. Duncan and Buchignani's [1] field observations show that shear modulus, G, is approxiamatley 50-500 times the undrained strength of soil, c_u. Several researchers [2–4] have accounted for compressibility of soils on ultimate bearing capacity of shallow foundations based on cavity expansion theories. Edwards et al. [5] conducted a finite element analysis of foundation soil, considering deformation modulus, E, as 500 and 2000 times that of undrained strength, c_u. McMahon et al. [6] propose a non-linear equation to estimate the bearing pressure of homogeneous soil for specific settlement, as a function of soil rigidity and shear strength.

The influence of soil heterogeneity on bearing capacity of footing has been analysed by several researchers based on plasticity theory [7, 8] and numerical analysis [9, 10]. It is observed that soil's heterogeneity with depth increases the bearing capacity of footings. Shiva Bhushan et al [10] studied the influence of compressibility on bearing capacity of circular embedded foundations accounting for heterogeneity.

The granular layer laid over compressible normally consolidated soils improves the bearing capacity and settlement response of footing due to shear layer effect and stress distribution through stronger and stiffer sand layer. Hanna and Meyerhof [11] proposed bearing capacity charts for sand overlaying soft soil, considering punching mechanism. Based on theory and test results on sand over clay [12–14], ultimate bearing capacity of foundations is shown to depend on relative bearing capacity ratio of soil layers, thickness of sand layer and the foundation's shape and depth.

Pham and Ohtsuka [15] adopted Rigid Plastic Finite Element Method (RPFEM) to predict the ultimate bearing capacity of rigid footings on sand over clay, as two-layered soils. Results are presented in the form of design charts for bearing capacity as a function of sand thickness and shear strength of clay. Ornek et al. [16] investigate the improvement of bearing capacity for circular footings placed on soft clay that has been improved by the addition of granular soil layers.

The current study investigates the influence of compressibility and heterogeneity in NC soils on bearing pressure-settlement response of circular footing on granular layer overlying normally consolidated soil. The effect of granular layer thickness on bearing pressure-settlement behavior of circular footing is also studied.

2 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 $c_0+\rho z$.

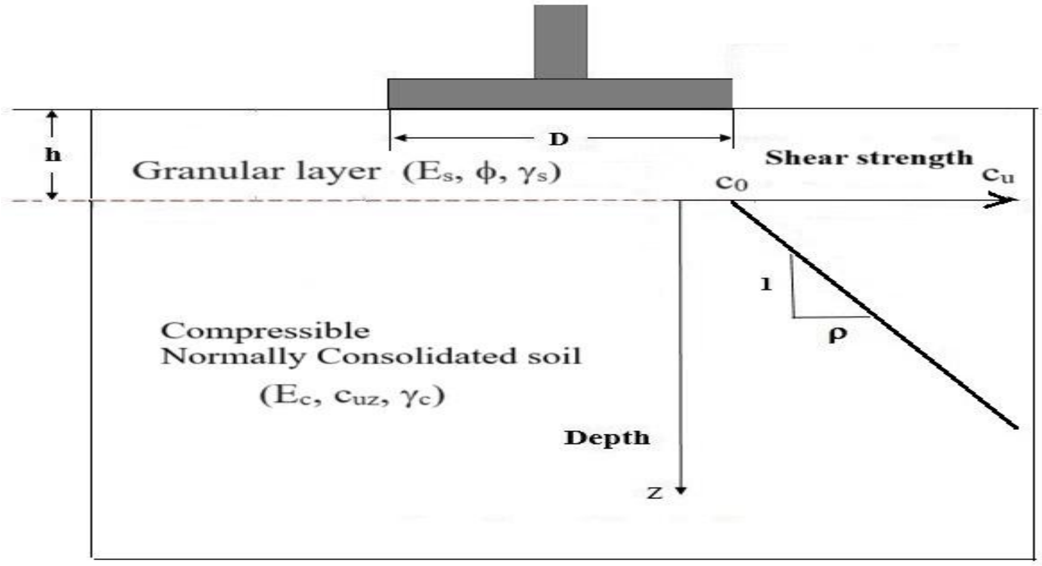


Fig. 1. Definition sketch of footing on granular layer over compressible NC ground

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.

3 METHODOLOGY

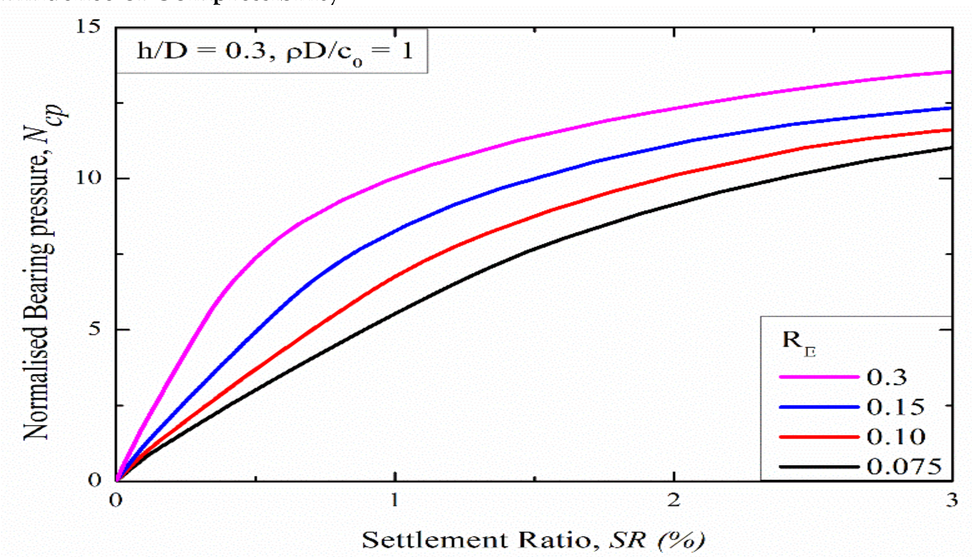
Axisymmetric finite element analysis was carried out using PLAXIS 2D software. Mesh geometry was 15 noded triangular elements. Vertical and lateral boundaries were positioned at six times the diameter of the footing. Lateral boundaries are fixed in radial direction, bottom boundary in both radial and 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 bearing pressure-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 pressure of GNC soil is obtained as a function of foundation settlement for individual parameters of the study.

4 RESULTS AND DISCUSSION

A circular footing of 5 m dia, D, resting on granular layer overlaying compressible NC soil is considered for the analysis. The bearing pressure for various prescribed settlements is normalised by undrained strength, c_0 as N_{cp} (= q/c_0), and settlement is normalised 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



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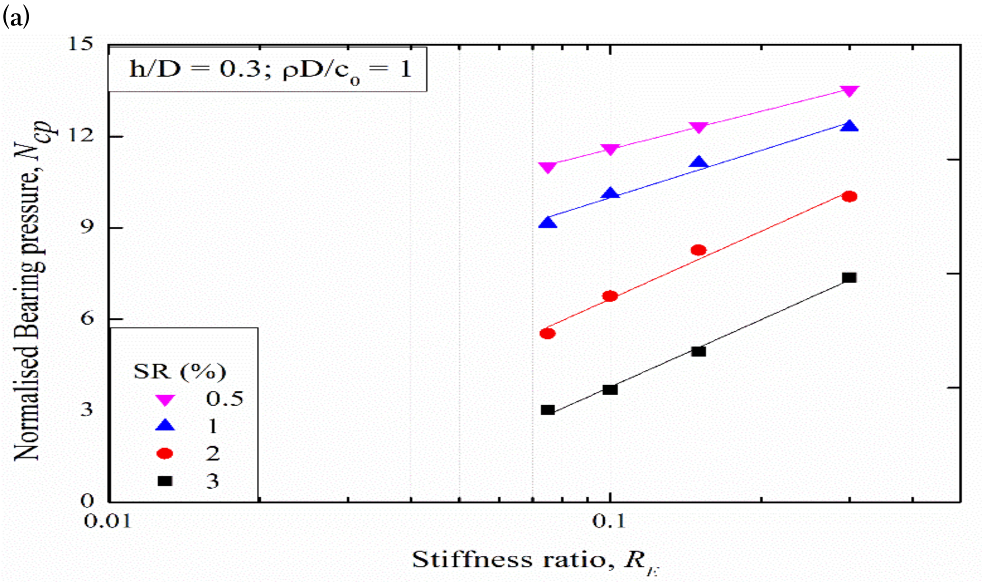


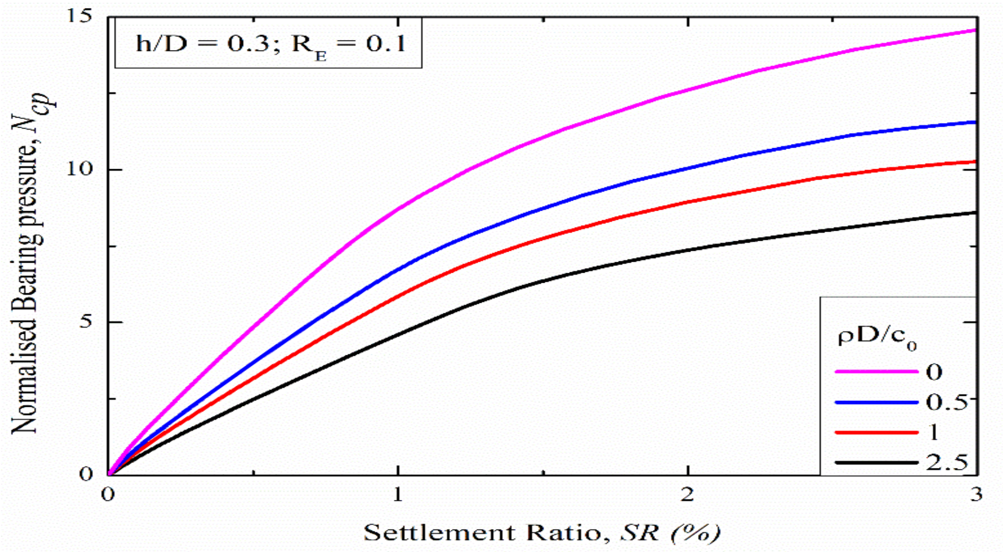
(b)

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

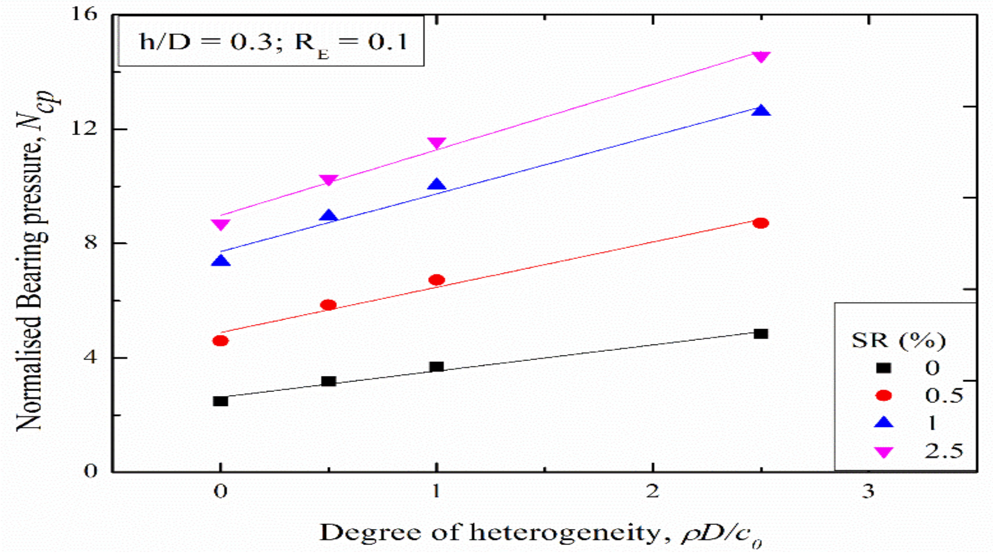
Figure **2(a)** presents the variation of normalized bearing pressure with settlement ratio for GNC ground for various deformation modulus of NC soil, for h = 1.5 m. The deformation modulus of clay is varied from 1500 to 6000 kPa, i.e., stiffness ratio, R_E values are taken as 0.075, 0.1, 0.15 and 0.3. GNC possessing relatively a larger stiffness ratio, e.g., 0.3, as expected resulted in higher bearing pressure. N_{cp} increases by 81% for 4-fold increase in the deformation modulus of NC soil, E_c, at SR = 1%. Normalized bearing pressure, N_{cp}, is plotted against the stiffness ratio of GNC soil, R_E, on semilog scale for different settlement ratios in Figure **2(b)**. N_{cp} varies linearly with R_E for a given foundation settlement. N_{cp} values increase with R_E significantly at smaller settlements. At SR = 0.5% and 3%, N_{cp} 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 pressure-settlement responses of circular footing on GNC ground for varying degrees of heterogeneity, $\rho D/c_0$, 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

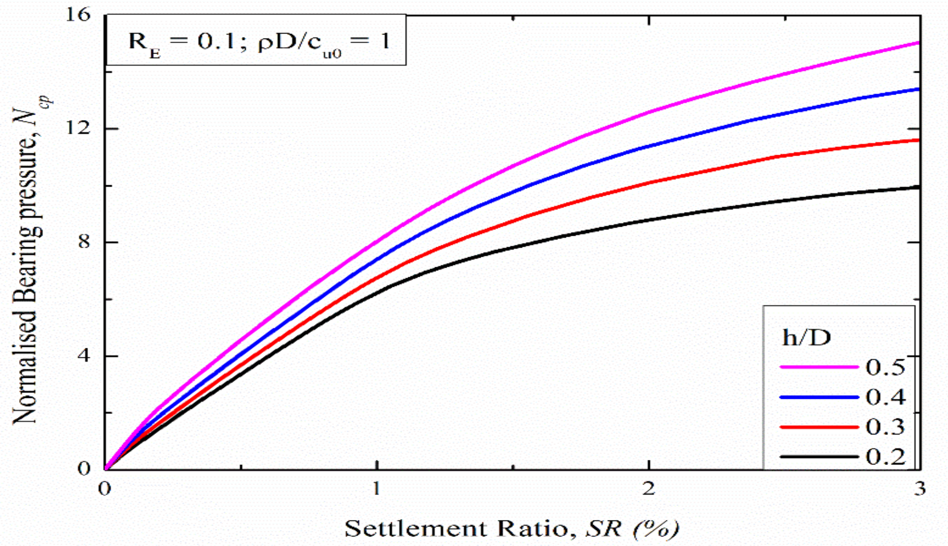
a) N_{cp} versus SR (%) at different $\rho D/c_0$ b) N_{cp} versus $\rho D/c_0$ at different SR.

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 pressure, due to contribution of layer's undrained strength. N_{cp} increases by 21% for 5-fold increase in $\rho D/c_0$, at SR = 3%. Normalised bearing pressure of footing, N_{cp} 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_{cp} increases linearly with $\rho D/c_0$ for a given foundation settlement. At SR =1% and 2%, N_{cp} increases by 24% and 20%, respectively for 5 times increment in the degree of heterogeneity in NC layer.

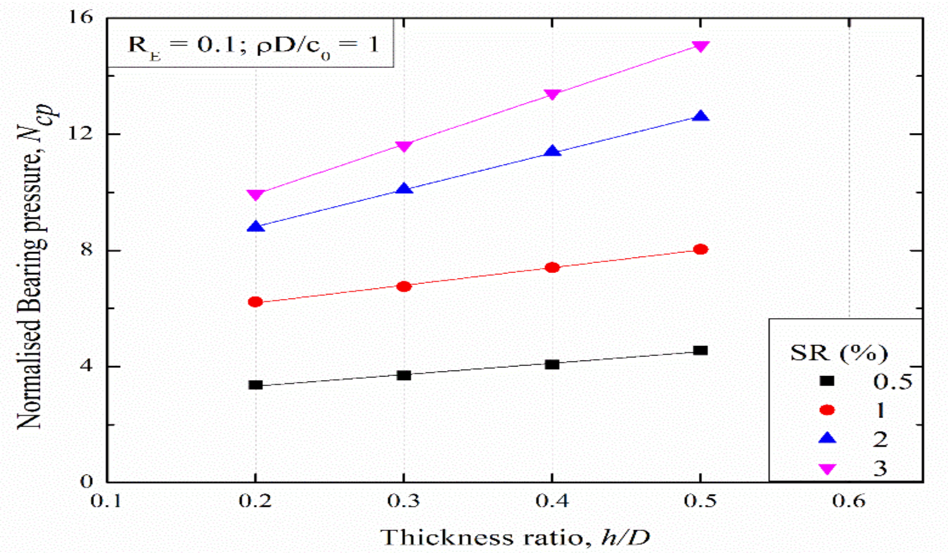
Influence of Granular Layer Thickness

Bearing pressure-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 pressure versus settlement responses obtained.

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



(a)



(b)

Fig. 4. Effect of thickness of granular bed

a) N_{cp} versus SR(%) at different h/D b) N_{cp} versus thickness ratio (h/D) at different SR

Variations of normalized bearing pressure 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 pressure values for a given footing settlement, contributing to shearing layer effect offered by granular strata. For SR = 1%, N_{cp} value increases from 6.22 to 8.03 for h/D increasing by 2.5 times. For SR = 0.5% and 3%, N_{cp} increases by 1.35 and 1.51 times, respectively, when the thickness of sand bed increases from 1.0 m to 2.5 m.

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

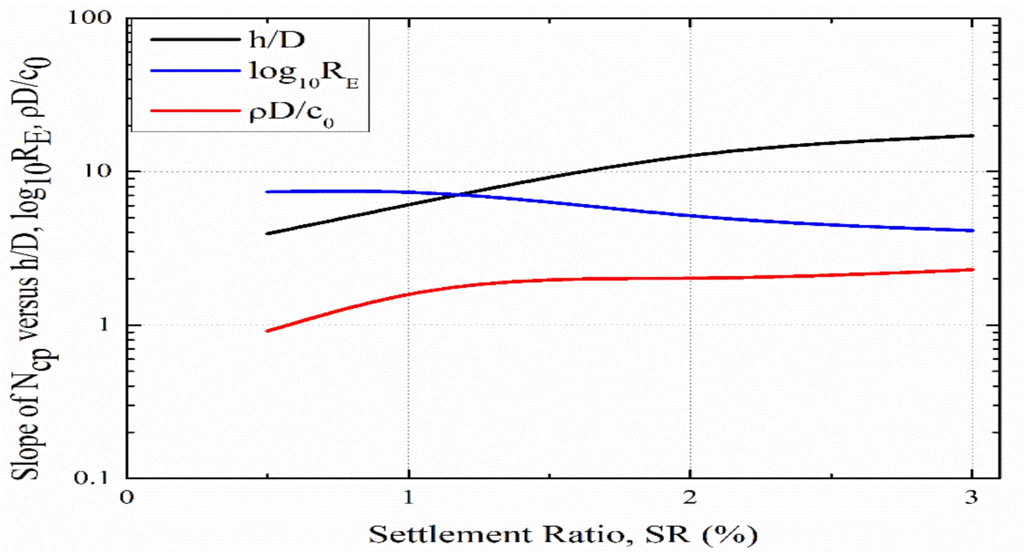


Fig. 5. Variation of slopes of N_{cp} versus different parameters with SR

5 CONCLUSIONS

Bearing pressure-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 pressure are quantified as function of settlement. Bearing pressure 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 pressure 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 pressure is more significant for a given foundation settlement compared to that for rigidity and heterogeneity of normally consolidated soil.

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