BEHAVIOUR OF ADJACENT STRIP FOOTINGS ON UNREINFORCED/REINFORCED GRANULAR BED OVERLYING CLAY WITH/WITHOUT VOID

Thesis

Submitted in partial fulfilment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

by

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NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA

SURATHKAL, MANGALORE – 575025

JUNE 2021

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D E C L A R A T I O N

by the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled "**Behaviour of Adjacent Strip Footings on Unreinforced/Reinforced Granular Bed Overlying Clay with/without Void"** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Civil Engineering**, is a *bonafide report of the research work carried out by me.* The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Date: 10-06-2021

C E R T I F I C A T E

This is to *certify* that the Research Thesis entitled **"Behaviour of Adjacent Strip Footings on Unreinforced/Reinforced Granular Bed Overlying Clay with/without Void"** submitted by **ANASWARA S**, (Register Number: **155023CV15F01**) as the record of the research work carried out by her, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of Doctor of Philosophy.

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ABSTRACT

In many situations, due to rapid urbanisation, such as lack of construction sites, structural and architectural restrictions, buildings are placed close to each other. In such cases, the stress isobars or the failure zones of closely spaced foundations may interfere with each other leading to the phenomenon called 'Interference'. It has an impact on the stresses in the subsoil due to overlapping of stresses, bearing capacities, settlements and tilts of footings due to the superstructure loads. Recognising the effects of interference and designing the footings accordingly ensures the safety and good performance of the structures.

The first part of this doctoral research work studies the interference effects of two/three-strip footings placed adjacent to each other on unreinforced/reinforced granular soils, including some experimental studies. Effects on stresses in foundation soil; bearing capacities, settlements and tilts of footings are being investigated. Parameters varied in this study are (i) Number of footings (In the case of two footings loaded simultaneously, both experimental and numerical studies are conducted. In the case of two footings loaded sequentially and three footings, numerical studies are done) (ii) Loading conditions (iii) Clear spacing between the footings and (iv) Number of reinforcement layers in foundation soil. With two footings, two loading conditions are considered. In the first loading condition, both the footings are loaded simultaneously up to failure. In the second loading condition, one of the footings representing an already existing foundation is loaded with half of the estimated failure load of single strip footing and adjacent footing loaded up to failure. It is observed that in the case of simultaneous loading, there is a certain critical spacing (S=2B) at which the footing/s carry the maximum load. At S/B=2, the interference effect improves the bearing capacity of the 50mm and 100mm footings by 37% and 74%, respectively. The effect of providing the reinforcements in layers in the foundation soil, beneath the footings, is seen in the increased bearing capacities, reduced settlements, and reduced tilts of the footings. Tilts are also found to be influenced by the loading conditions. On unreinforced soil, increasing the distance from 1B to 4B between the footings results in a nearly 12% reduction in tilt in interfered footing. At S/B=2, introducing three reinforcing layers beneath simultaneously loaded interfering footings results in a 2.6 per cent tilt reduction. In the case of sequential loading of old and new footing, providing reinforcement beneath the new footing and loading it to maximum, causes a somewhat larger tilt (6.32% increment) of already existing strip footings.

As the second part of this doctoral research work, numerical studies are undertaken on the behaviour of two adjacent strip footings on unreinforced (GB) and reinforced granular bed (RGB) overlying clay with/without voids. The influence of different parameters such as granular bed thickness, length of reinforcement/s, number of layers of reinforcement, presence of void/s beneath the footing/s in the weak soil etc., on the behaviour of footings are carried out. With two adjacent strip footings on GB overlying weak soil, the bearing resistance of each footing is more (14% for B=1m and 36% for B=2m) than a single independent strip footing on GB overlying weak soil.

The voids could be formed in weak soil due to various reasons, and the presence of voids will affect the performance of footings. Such voids tend to reduce the load-carrying capacity of the footing/s and alter the failure pattern of foundation soil. In the case of a single void under two footings, the maximum reduction in the bearing capacity of new footing (53% reduction for B=1m, H/B=1) is reported when the void is formed directly below the new footing. When a void is formed anywhere beneath the footing/s in the weak soil, either directly beneath or nearby close to the centre line of the footing/s, failure surfaces developed from the nearest footings tend to move towards the void and are found to be narrower than the no void case. However, providing a reinforced granular bed (RGB) over weak soil can be used as an effective method to maintain the good performance of footings, even when voids could be formed in future. The interference effect in top granular soil combined with the reinforcement effect is seen to effectively nullify the void effect. This research work attempted to provide an analytical model to estimate the ultimate bearing capacity of two and three adjacent strip footings resting on granular bed overlying weak soil, with a fair and acceptable degree of accuracy. The accuracy of the proposed model has verified with finite element simulations and the percentage error is about 13%.

Keywords: Interference; Strip footing; Bearing capacity; Tilt; Settlement; Void; Geogrid

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NOMENCLATURE

List of Abbreviations

ΔBCR_{CE}	Improvement in Bearing Capacity Ratio due to confinement effect
ΔBCR_{SE}	Improvement in Bearing Capacity Ratio due to additional surcharge effect
ΔBCR_{SL}	Improvement in Bearing Capacity Ratio due to shear layer effect
ΔBCR	Improvement in Bearing Capacity Ratio
BCR	Bearing Capacity Ratio
EA	Axial stiffness
GB	Granular Bed
H/B	Normalised thickness ratio
IRF-RGB	Improved Reduction Factor
MBCR	Modified Bearing Capacity Ratio
RF	Reduction Factor
RF-GB	Reduction Factor defined in Granular Bed
RF-RGB	Reduction Factor defined in Reinforced Granular Bed
RGB	Reinforced Granular Bed
SP	Poorly graded soil

Notations

B	Footing width
c	Cohesion
D_{10}	Effective grain size
E	Young's modulus
H	Thickness of upper soil layer
$\frac{H}{B}$	Normalised thickness ratio
IF'_1	Interference Factor of bearing capacity- Simultaneously loaded-layered soil
IF'_2	Interference Factor of bearing capacity- Sequentially loaded-layered soil

IF'_{V1}	Interference Factor of bearing capacity with void-Simultaneously loaded
IF_1	Interference Factor of bearing capacity- Simultaneously loaded
IF_2	Interference Factor of bearing capacity- Sequentially loaded
IF_C	Interference Factor due to combined effect of interference and reinforcement
IF_{CV}	Interference Factor due to combined effect of void and reinforcment
IF_r	Interference Factor with reinforcement
IF_{rv}	Interference Factor with reinforcement and void
IF_{V1}	Influence Factor of bearing capacity with void-Simultaneously loaded)
IF	Interference Factor
IF_{V2}	Influence Factor of bearing capacity with void-Sequentially loaded)
k_s	punching shear coefficient
N_C, N_γ, N_ϕ	Bearing capacity factors
q_{CE}	Bearing capacity due to confinement effect
q_S	Ultimate bearing capacity of sand
q_{SE}	Bearing capacity due to additional surcharge effect
q_{SL}	Bearing capacity due to shear layer effect
q_c	Ultimate bearing capacity of clay
q_u	Ultimate bearing capacity of soil
q_u'	Ultimate bearing capacity of soil with void
q_{u0}	Ultimate bearing capacity of an independent strip footing on layered soil
R	Number of layers of reinforcement
S	Clear spacing between the footings
s	Settlement
s_u	Undrained shear strength
$\frac{S}{B}$	Spacing ratio

$\frac{s}{2B}$	Normalised settlement
T_R	Reinforcement force
$\frac{X}{B}$	Eccentricity ratio
$\frac{Y}{B}$	Depth ratio
$\overline{\phi_s}$	Increased friction angle
$\overline{\gamma_s}$	Increased density
ϕ_R	Friction angle between the reinforcement and granular soil
ϕ_{sand}	Angle of internal friction of sand
γ_s	Unit weight of sand
ξ_δ	Interference factor due to settlement
σ'_{xx}	Effective horizontal pressure
σ'_{yy}	Effective vertical pressure
τ'_f	Mobilised shear resistance developed at the densified soil side
τ_f	Punching shear resistance along a vertical plane due to shear layer effect
α	Load spread angle
ν	Poisson's ratio
Ψ	Dialatancy angle

CHAPTER 1

INTRODUCTION

1.1. GENERAL

All structures, whether on the ground or above ground or below the ground, are ultimately supported by the ground. The footing is a part of an engineered system, an interface, that transmits the loads from structure to the underlying ground comprising of soil and/or rock. It results in the development of stresses in foundation soil in addition to those pre-existing stresses in the earth mass from its self-weight and geological history. A Geotechnical engineer is concerned with the two problems of assessing the ability of the soil to support the loads and designing the proper transition members to transfer the superstructure loads to the subsoils. Foundations are designed based on two criteria, namely Bearing Capacity and Settlement criterion. The soil must be capable of carrying the structural loads without a shear failure and with the resulting settlement being tolerable for the structure placed upon it.

In many situations such as rapid urbanisation, lack of construction sites, structural and architectural restrictions, buildings are placed close to each other. In such cases, the stress isobars or the failure zone of closely spaced foundations may interfere with each other leading to the phenomenon called 'Interference'. It has an impact on the stresses in the subsoil, bearing capacity, settlement, failure mechanism and tilt of footings subjected to vertical loads, either centric or eccentric. Stresses on the subsoil, stress overlapping, bearing capacity and settlement of footings are the essential criteria that influence the design of the footings affected by the presence of one or more of the footings close to each other. The interference effect generally depends on the factors such as spacing between the footings, applied load intensity, soil properties, footing shape and size etc. The conventional methods of foundation design assume the footings are free from adjacent foundations. Therefore, the study of the behaviour of closely spaced interacting footings is of paramount practical importance in the field of sub-structural engineering to achieve economical and safe designs.

1.2. REINFORCED SOIL

Soils are strong in compression and shear, but weak in tension. Reinforced soil is a composite material that is formed by the combination of any soil (preferably cohesionless soil) and tension resistant elements in the form of sheets, strips, nets or mats of metal, synthetic fabrics or fibre reinforced plastics and various other types. These tension elements are arranged in the soil mass in such a way as to reduce or suppress the tension strain, which might develop in the soil mass. Reinforcements are thin elements with a normal stiffness but with no bending stiffness. We can get many examples of reinforcement techniques from nature. Beavers build dams of mud reinforced with hay grasses, tree trunks and stones to ensure greater stability and to ensure that these do not freeze.

These days weak grounds are improved by reinforcing the foundation soils to improve bearing capacity, reduce settlements and improve the performance of the structure. Few studies on the bearing capacity due to interfering footings on a reinforced soil have been carried out (Kumar and Saran 2003, Ghazavi and Lavasan 2008, Lavasan and Ghazavi 2012, Noorzad and Manavirad 2014, Naderi and Hataf 2014, Biswas and Ghosh 2018). The topic of interference has not been comprehensively investigated, especially in the case of reinforced soil foundations. Therefore, paying attention to estimate the behaviour of interference effect on a foundation in the case of reinforced soil foundations, seems justified.

1.3. LAYERED SOIL

Geotechnical engineers often deal with layered soil system either naturally available or created by man which is non-homogeneous. Numerous studies have been done on the interference effect of footings, but most of the studies are done on homogeneous soils, especially cohesionless medium (Stuart 1962, Das and Larbi-cherif 1983, Selvadurai and Rabbaa 1983, Kumar and Saran 2004, Kumar and Ghosh 2007, Ghazavi and Lavasan 2008, Lavasan and Ghazavi 2008, Kumar and Bhoi 2009, Lavasan and Ghazavi 2012, Kouzer and Kumar 2010, Lavasan et al. 2017, Gupta and Sitaram 2020). However, in actual practice soil mass is non-homogeneous and anisotropic.

Quite often low-lying areas with clayey soil (or weak soil) are provided with granular fill (granular bed) on top. This granular fill (Granular Bed (GB)) serves two purposes such as raising the ground level to the nearby road level and secondly it increases the allowable load onto the filled-up ground from the superstructure. Adding reinforcement in the fill, i.e. providing a reinforced granular bed (RGB) will further enhance the load-bearing capacity and reduce the settlements. The analysis of footing interference on layered soil system also needs a relook, especially in the context of an upper reinforced layer.

1.4. EFFECT OF FORMATION OF VOID

The weak soil could contain voids. Voids could be formed prior to or after the construction. Voids could be formed in weak soil strata due to various reasons such as due to water leakage from the water supplying lines or sewer lines and erosion of soil, animal burrows etc. Foundations over voids are a severe engineering problem, especially when the voids are near the ground surface. Most of the previous studies focused on the effect of void on the performance of isolated footings (Baus and Wang 1983, Badie and Wang 1984, Wang and Badie 1985, Wang and Hsieh 1987, Azam et al. 1991, Kiyosumi et al. 2007, Kiyosumi et al. 2011, Lavasan et al. 2016).

The first part of this doctoral research work studies interference effects of two/three-strip footings placed adjacent to each other on unreinforced/reinforced granular soils, including some experimental studies. Effects on stresses in foundation soil; bearing capacities, settlements and tilts of footings are being investigated. Parameters considered in this study are (i) Number of footings (In the case of two footings loaded simultaneously, both experimental and numerical studies are conducted. In the case of two footings loaded sequentially and three footings, numerical studies are done) (ii) Loading conditions (iii) Clear spacing between the footings and (iv) Number of reinforcement layers in foundation soil.

As the second part of this doctoral research work, numerical studies are made on the behaviour of two adjacent strip footings on unreinforced (GB) and reinforced granular bed (RGB) overlying clay with/without voids. The influence of different parameters such as granular bed thickness, length of reinforcement/s, number of layers of reinforcement, presence of void/s beneath the footing/s in the weak soil etc., on the behaviour of footings are carried out. A simple analytical model is also attempted to predict the bearing capacity and interference factor of two and three adjacent strip footings on GB overlying clay.

1.5. OBJECTIVES AND SCOPE OF RESEARCH

In recent times, due to rapid developmental activities and scarcity of land, especially in the urban areas, demand for construction sites in good commercial areas are increasing at a rapid rate. Land prices are soaring sky high. The land which is categorised as nonsuitable for construction also has to be utilised and made suitable by any of the ground improvement methods. Several structures are built close to each other, and hence their closely spaced foundations often interfere with each other. 'Interference' affects stresses in foundation soil, load-carrying capacity of footings, settlements and tilts of footings. The increment in bearing capacity is a positive effect but settlement and tilt increment are negative effects of interference. The excessive settlement could cause distress in buildings. Tilts could cause cracks between the wall and the foundation or between the wall and the roof slab. The interference effect is not considered in the design of footings.

Construction of a new footing adjacent to the old footing will alter the bearing capacity, settlement, rotational characteristics and failure mechanism of the latter. Also, nowadays with the advent of new construction materials like geosynthetics, an attempt has been made to study the influence of placing geogrid reinforcements beneath a new footing which is built adjacent to an already existing (old) foundation.

These days weak grounds are improved by the granular bed (GB) or reinforced granular bed (RGB) to improve bearing capacity, reduce settlements and improve the performance of the structure. The presence of voids could affect the performance of footings, especially if the voids are present within the influence zone of the footing. The influence of voids below interfering footings has not received much attention. The topic of interference has not been comprehensively investigated, especially in the case of reinforced layered soil foundations.

Most previous studies in the literature which studied interference effects of adjacent strip footings on granular bed overlying weak soil have not provided an analytical model. This research work attempted to provide an analytical model to estimate the ultimate bearing capacity of two and three adjacent strip footings resting on granular bed overlying weak soil, with a fair and acceptable degree of accuracy.

The main objectives set for the present work are

- To perform a few laboratory-scale experiments which will be compared by numerical analysis. Also, to validate the numerical study with some experimental results available in the literature.
- To study the interference effect between closely spaced strip footings on unreinforced/ reinforced granular bed overlying weak soil, mainly by numerical analysis. The different parameters are (i) Spacing between the footings (ii) Types of loading conditions as simultaneous and sequential loading of strip footings (iii) Thickness of the top layer of granular soil bed (iv) Width of the footings (v) Properties of soil like cohesion, angle of friction(vi) Number of reinforcement layers (vii) Length of reinforcements (viii) Connectivity between the reinforcements, i.e., continuous or discontinuous (ix) Presence of voids in the weak foundation soil.
- To study the effect of various parameters listed above in the case of layered soil on interference.

1.6. ORGANISATION OF THESIS

The thesis is organised in the following manner to explain the direction taken to achieve the objectives of this project.

Chapter 1 of this thesis gives a general introduction to interference and its various aspects. It also provides a brief introduction to the reinforced soil system, layered soil and the effect of voids. This chapter states the objectives, and scope of this research work.

Chapter 2 reviews the literature relevant to the determination of bearing capacity, settlement, tilt and failure mechanism of adjacent footings. Also, this chapter reviews past studies and researches on layered soil and the effect of void on the performance of footings. The literature dealing with the various methods like experimental studies, numerical studies and analytical modelling on interference effect are reviewed.

Chapter 3 outlines the methodology of the research to achieve the objectives. This chapter discusses the methodology of experimental and numerical analyses in detail. Laboratory scale plate load tests conducted on the unreinforced and reinforced soil samples, and the load-settlement characteristics of these soil samples are studied. The details of the load test apparatus and the test procedure conducted are discussed in this chapter. The experimental test results are compared with PLAXIS 2D. Interference effects on homogeneous and layered soils done in PLAXIS 2D considering different parameters are discussed in this chapter. Further, the methodology adopted for the numerical analysis of interference studies and the details of the modelling procedure are elaborated.

Chapter 4 deals with the analysis of the experimental and numerical results. The results of the study are presented and discussed with reference to the main aim of the study. The comparison of results obtained from the experimental study and finite element analysis are detailed in this chapter. Interference effects of adjacent footings on granular bed overlying weak soil with/without voids are also discussed in this chapter.

Chapter 5 gives the details of the development of a simple model to predict the load-carrying capacity of an interfered footing, and the interference factor, when adjacent strip footings are placed on the surface of a Granular Bed (GB) overlying clay with no void, and the footings are simultaneously loaded. The comparison between the bearing capacity and interference factor calculated by the proposed model and those obtained from finite element studies are presented in detail. It is observed that the proposed analytical model predicts the values of bearing capacity and interference factor values with reasonable accuracy.

Chapter 6 deals with the numerical analysis of the two adjacent strip footings on sands (loose, medium and dense sands) and clays (soft, medium and stiff clays). The effects of the shear key beneath the footing are also studied.

Chapter 7 concludes the thesis with a summary of the research work. The findings of the laboratory scale plate load test, numerical analysis and analytical modelling are summarised. This chapter includes major contributions of the work, recommendation section and also discusses the future scope of the work.

CHAPTER 2

REVIEW OF LITERATURE

2.1. GENERAL

The interference of the footings is observed when two footings are closely spaced, and the stress isobars of the individual footings interfere. Interference leads to changes in different characteristics of the footings, such as bearing capacity, settlement, tilt, etc… Numerical analyses and experimental studies were carried out by many researchers to understand better the effects of interference of two or more closely spaced footings.

2.2. INTERFERENCE EFFECT ON CLOSELY SPACED FOOTINGS

Figure 2.1 explains the possible consequences of strip footings placing closer to each other. At 'a' no interference takes place because footings are at wide spacing and total load also twice that of taken by single footing. When spacing is reduced 'b' occurred, where passive zones interpenetrate and no change in ultimate load at failure. A closer spacing like that in 'c' the size of the passive zone between the footings curtailed and resulted in the different stress values. The last case 'd' occurred before the footings come into contact. At this spacing, the blocking effect occurs, and the pair will act as a single foundation. Blocking effect means when two footings at close spacing, the soil between them are locked between adjacent edges of the close foundations. Thus, the stress level is increased in this zone by an increase in load applied to the foundations. The stress is concentrated at the edges of the footings. A block is formed in the confined soil between the foundations. This phenomenon results in the formation of a rigid confined block in space between foundation results in increases in bearing capacity. When footings touch, this zone disappears and the system act as a single footing of width 2B.

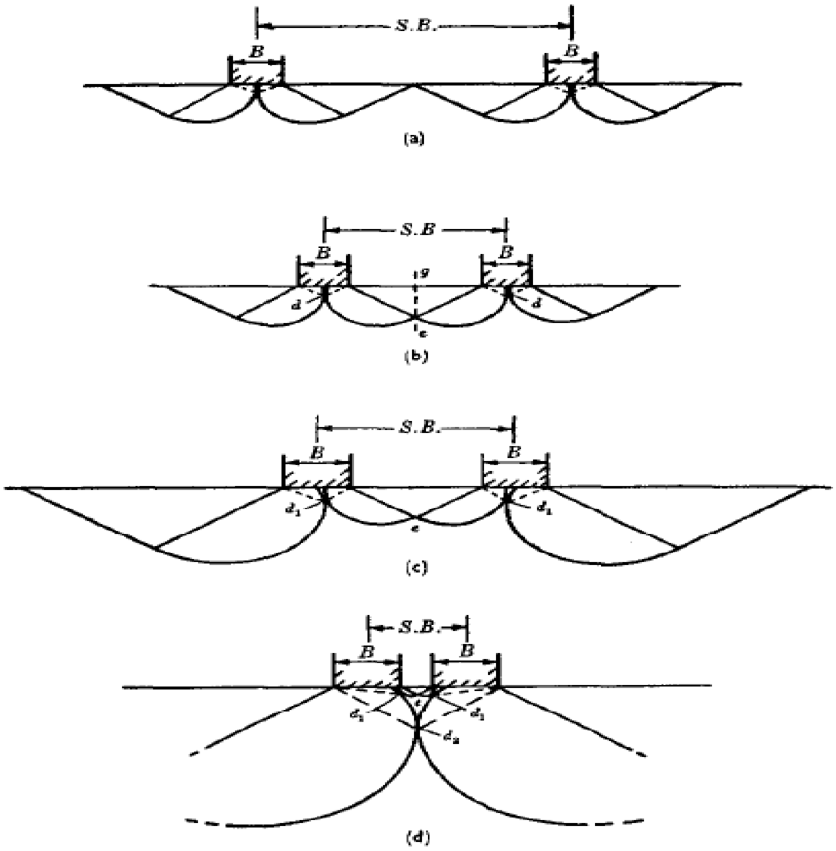


Figure 2.1. The development of the failure surfaces as two rough–based foundations approach each other on the surface of cohesionless soil (Stuart, 1962)

2.2.1. Bearing Capacity

Most of the prior studies are focused on the ultimate bearing capacity of the interfering footings. Interference of adjacent footings can cause changes in load settlement characteristics and bearing capacity when compared to the single footing. The interference effects of shallow foundations were first studied by Stuart (1962). Stuart (1962) examined the effect of interference on the stresses and stress zones of two closely spaced strip footings resting on the surface of the cohesionless medium and found out that it leads to a change in ultimate bearing capacity. Experimental and limit state methods were used, and an equation was proposed for calculating bearing capacity with the interference effect by the inclusion of efficiency factors, ξq, and $\xi \gamma$. These coefficients depend on the angle of friction of sand, and the distance between the foundations, the variation of efficiency factor was computed with respect to the change in the clear spacing between the footings. The efficiency factor was defined as the ratio of the ultimate failure load of a single footing in the presence of the other footing to that of the single isolated footing of the same size. To obtain the ultimate bearing capacity (per unit length) of one of a pair of interfering footings (Q_b) explained as follows.

$$Q_b = \gamma B^2 N_{\gamma q} \quad (2.1)$$

where Q_b-load at failure/unit length, B-width of the foundation, $N_{\gamma q}$ -bearing capacity coefficient, which is a function of depth breadth ratio and ϕ.

The study of Stuart (1962) was further extended by West and Stuart (1965). West and Stuart (1965) worked to find a simple method of estimating eccentricity ‘e’ and inclination ‘λ’ of the resultant soil reaction of a pair of shallow rough based strip foundations. The amount of eccentricity ‘e’ and inclination ‘λ’ will be a function of the degree of asymmetry of the failure mechanism and hence will be directly related to the efficiency characteristics of the pair of foundations.

Das and Larbi-Cherif (1983) conducted laboratory tests on two closely spaced strip footings on sand and compared their experimental results with the theoretical equations presented by Stuart (1962). It was found that experimental data for the bearing capacity of interfering strip footings were substantially lower than those given by theory.

Agrawal (1970) studied the interference of adjacent surface footings on the sand by model tests. Both the two dimensional and three-dimensional tests were conducted on square and rectangular footings. All the tests were conducted on uniform dry Ranipur sand compacted at a relative density of 75%. Results obtained from these tests indicated that the bearing capacity factor $N\gamma$ decreases as the spacing increases up to certain spacing (4.75B) and then shows a slight increase in bearing capacity after a further increase in spacing.

Selvadurai and Rabbaa (1983) presented an experimental study of the problem of interference between two closely spaced rigid strip foundations resting on a layer of granular soil. Using the reduced single footing approach experiments were performed to investigate the influence of interference on the load-displacement relationship and the contact stress distribution of two rigid footings resting on a layer of sand. The contact stress distributions are of particular importance to the structural design of footings resting on granular soil. In conventional structural design calculations, the contact stress distribution beneath a centrally loaded footing is assumed to be uniform. The results of this series of experiments indicate that when footings approach each other, the contact stress distribution is no longer uniform.

Harrop-Williams and Grivas (1985) studied the interference between geotechnical structures. If a footing is constructed near a soil slope, the relative safety of the footing not only depends on the amount of overlapping of their failure surfaces but also the probability of failure of the slope. This study presented a simple procedure to determine the degree of dependence between adjacent geotechnical structures.

The estimation of bearing capacity and tilt were done from the pressure-settlement characteristics of the foundation soil by Verma (1986) on clay and sand. The soil below the footings divided into a large number of thin strips and stresses and strains in each strip considered uniform at every section. The results obtained from the analysis indicate that bearing capacity increases as the spacing decreases up to certain spacing and then shows a slight decrease in bearing capacity after further reduction in spacing.

Two different possible failure mechanisms were considered by Kumar and Ghosh (2007) for the ultimate bearing capacity of two interfering strip footings analysis. Mechanism 1 was based on the employment of a quadrilateral trapped wedge below the base of each footing. In contrast, a non-symmetrical triangular wedge was considered below each footing in mechanism 2 (Figure 2.2). The results from mechanism 2 provided a better comparison with the theory of Stuart (1962).

Kumar and Kouzer (2008) used upper bound limit analysis in conjunction with finite elements and linear programming to compute the ultimate bearing capacity of two interfering rough strip footings, resting on a cohesionless medium. When there is no gap between the two footings, the efficiency factor becomes two. It indicates that the average ultimate bearing pressure on an intervening footing becomes twice that of an isolated footing of the same width.

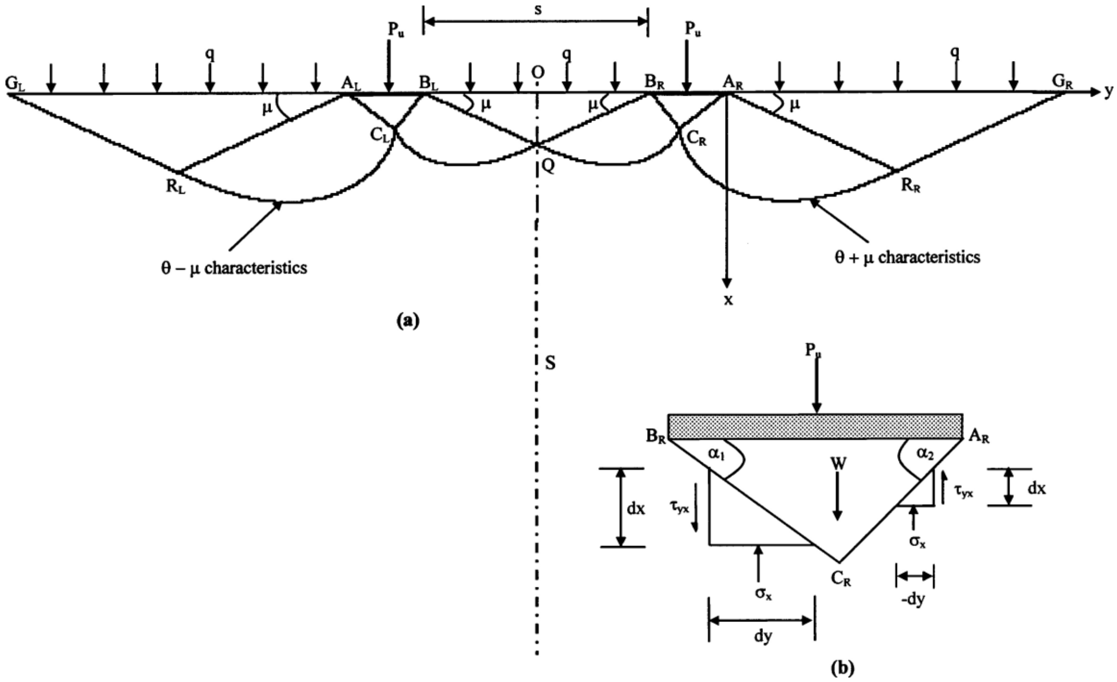


Figure 2.2. (a) Failure mechanism 2, (b) free body diagram of the trapped wedge (Kumar and Ghosh, 2007)

Kumar and Bhoi (2009) have done model tests on the sand to determine the interference effect of two closely spaced strip footings. With the simulation of the axis of symmetry, only one footing was needed in the experimental setup. The bearing capacity was maximum at a certain critical spacing between two footings. Relative density was found to influence the interference effect.

According to Lavasan and Ghazavi (2012), the occurrence of interference was found to have an important role in the ultimate bearing capacity, settlement, tilt and the failure mechanism of the footing. These effects were maximised when the spacing between neighbouring footings was about 1.5B.

Islam and Gnanendran (2013) studied the behaviour of two closely spaced strip footings placed on a stiff clay bed under cyclic loading. The study showed that the application of low-frequency cyclic load improves the bearing capacity and stiffness of foundation soil (clay), irrespective of the interfering footing spacing. Also, the permanent deformation of interfering footings placed at closer spacing is found to be smaller compared to that of footings placed at wider spacing

Naderi and Hataf (2014) conducted experimental and numerical analysis on two closely spaced circular and ring footing. The ultimate bearing capacity was most significant when the closely spaced circular and ring footings stand exactly beside each other and decreased with an increase in the spacing to footing diameter ratio. Footings were found to act independently when the centre-to-centre distance was more than 4D. Figure 2.3 shows stresses under footings and the interfering effect on them.

Nainegali and Ekbote (2019) studied the behaviour of two closely spaced strip footings resting on the surface of the semi-infinite clay soil medium. The bearing capacity was found to decrease with the decrease in clear spacing between the footings. About the ultimate bearing resistance, the impact of footing interference on the pure clay medium is quite insignificant, while the impact is significant concerning the bearing capacity and the settlement measured in the allowed range.

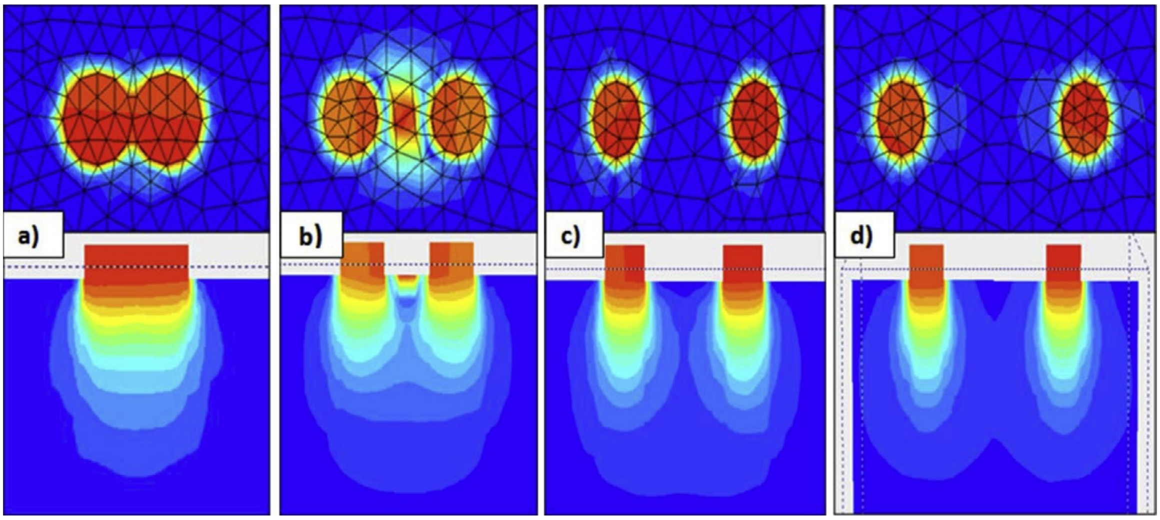


Figure 2.3. Total displacement of interfering circular footings in plan and section views for different spacings: a) Δ/D=1, b) Δ/D=2, c) Δ/D=3, d) Δ/D=4 (Δ-centre to centre spacing between the footings, D-Diameter of footing) (Naderi and Hataf, 2014)

Lavasan et al. (2018) examined the ultimate bearing capacity of two closely spaced rigid strip footings with a rough base on granular soil, based on enhanced limit equilibrium, plastic limit analyses, and finite-difference solutions. The enhanced limit equilibrium and plastic limit analyses were developed based on two proposed failure mechanisms in association with an optimisation algorithm. The efficiency factors of bearing capacity were calculated at the various spacing between two neighbouring footings for the practical range of friction angles ($25° \leq \Phi \leq 40°$) by different solutions.

Ahmed and Ali (2018) analysed important aspects of soil-foundation interaction of adjacent strip footings on saturated clay by a finite element modelling. It was shown that within a threshold distance between these foundations, an essential modification of the foundation behaviours might occur. Based on the numerical results, a simple, practical formula for the shallow foundation design was proposed.

Shokoohi et al. (2018) applied finite element and limit equilibrium methods to investigate the bearing capacity of adjacent strip footings. A series of correction factors were presented which represent the effect of neighboring two footings and they can be used to find the reduced and/or increased bearing capacity.

Fuentes et al. (2019) performed numerical analyses on closely spaced square footings on granular soils. The statistical analysis revealed that the efficiency factors dependent on the embedment depth and footing's separation.

Gupta and Sitaram (2020) conducted experimental and numerical studies in closely spaced square footings resting on loose, medium and dense sand beds. The interference factor was maximum in the case of S/B=0.5 and dense sand. This study concluded that the interference factor depends on the spacing between the footings and the angle of shearing resistance. They attributed interference to an increase in confining pressure due to the interaction between the failure zones of interfering footings.

2.2.2. Non-Identical Footings

In the presence of an established strip footing, Kouzer and Kumar (2010) calculated the ultimate bearing potential of a new strip footing positioned on a cohesionless soil medium. It was presumed that both the footings are completely rigid and rough. Using an upper bound finite element limit analysis, the analysis was carried out. The efficiency factor values were calculated for different clear spacing (S) between the footings. The increase in efficiency factor becomes further significant, with an increase in the magnitude of the load on the existing footing.

Nainegali et al. (2013) considered symmetric and unsymmetric cases with respect to geometry and loadings in the analysis for closely spaced strip footings. Settlement of interfering footing is found to be greater than isolated footing of the same width.

Ghosh et al. (2017) used the Pasternak model to determine the interaction effect of two closely spaced interference effect on asymmetric strip footings. The study was performed using both linear and nonlinear elastic analysis. This study found that the interference effect was more on the footing of smaller width. In the case of two footings with asymmetric loading, the interference effect was more for the footing with a smaller load. The smaller footing experiences more bearing pressure and less settlement than those of the larger footing.

Nainegali et al. (2018) studied the interference of strip footings resting on a nonlinearly elastic foundation bed by finite element analysis. Two interfering strip footings lying on the surface of a nonlinearly elastic soil (dense/loose sand) medium (symmetrical and asymmetrical with respect to footing size) are considered. Studies have shown that interference has a much greater effect on the response of the isolated footing in dense sand compared to loose sand. For asymmetrical footings at closer spacing, the interference effect is more pronounced for footing with small size. The variation of pressure-interacting factors measured in the allowable range is found to be similar to that measured at the ultimate failure. But the settlement-interacting factors are found to be different. Settlement interacting factors are the ratio of settlement of left/right footing, corresponding to allowable pressure of isolated footing with same properties to that of allowable settlement

Experimental studies were made by Salampatoor et al. (2019) on unequally loaded and sequentially constructed footings to study interference-effect. The footings are loaded unequally and non-simultaneously to simulate the mechanism of the new and the old footing with different surcharge and construction orders. It was observed that the interference of two adjacent footings (old and new) resulted in increasing the ultimate bearing capacity of the new footing. In contrast, it leads to an increase in settlement and tilt of older footing. It was also found that changing the safety factor of the old footing from 2 to 3 has a negligible effect on the tilting of the two interfering footings.

Schmu¨dderich et al. (2020) studied the influence of an existing footing on the bearing capacity of a new footing by finite element limit analysis. The findings show that it is possible to establish two forms of failure mechanisms that either reach the front edge of the existing footing or pass underneath. The design charts were presented for the estimation of the interference factor for existing footing for variable parameters.

2.2.3. Reinforced Soil

Experimental work on the bearing capacity of single shallow foundations on soils reinforced with geogrids and other materials have been studied by Dash et al. (2003), Alamshahi and Hataf (2008), Madhavilatha and Somwanshi (2009), Tafreshi and Dawson (2010), Demir et al. (2012), Abu-Farsakh et al. (2013) and many others. Finite element studies and numerical/analytical modelling of reinforced soils have been studied by Yamamoto and Otani (2002), Deb et al. (2007), Sharma et al. (2008), Pawar and Goyal (2015), Hussein and Meguid (2016) etc…

Kumar (1997) studied the interaction of footings resting on reinforced earth slab and found out that in the case of interfering footings resting on reinforced soil, the magnitude of settlement and tilt decreases for a given load intensity as compared to the same footings on unreinforced soil for the same load intensity.

Kumar and Saran (2003) conducted small scale model footing tests to study the interference effect on square and strip footing on geogrid-reinforced sand. They concluded that bearing capacity increases in closely spaced footing with the provision of footing size reinforcement layers in the foundation soil beneath the footing and interference effect was more predominant in strip footing compared to the square footing. Bearing capacity, settlement and tilt were considerably enhanced by providing continuous reinforcement layers in the foundation soil under the closely spaced strip footings.

Kumar and Saran (2004) suggested an approximate empirical method to compute the ultimate bearing capacity of adjacent footings resting on reinforced earth slab. The normal force on the reinforcing layer area and interfacial friction coefficient at different reinforcing layers are two critical stages in the computation of pressure ratio. Pressure ratio is the ratio of average contact pressure on reinforced soil at settlement Δ to that of the average contact pressure of footing on unreinforced soil at a settlement Δ. The non-dimensional charts also provided to aid in the computation process.

Ghazavi and Lavasan (2008) numerically studied the bearing capacity of square interfering footings constructed on the surface of sand reinforced with geogrids. The efficiency of the reinforcement in increasing bearing capacity was observed to be more in interfering footings compared to the isolated footing. The blocking effect disappears around Δ/B >2 and bearing capacity becomes maximum at about Δ/B =2, where Δ indicates centre to centre distance between footings and B indicates footing width. The bearing capacity of interfering reinforced footings increase by 1.5 and 2 for one and two reinforcement layers. I_f is the interference factor used to evaluate the bearing capacity of an interfering footing on reinforced soil is defined as

$$I_f = \frac{q_{uint(reinforced)}}{q_{usingle(unreinforced)}} \tag{2.2}$$

where $q_{uint\,(reinforced)}$ - Ultimate bearing capacity of interfering footing on reinforced soil, $q_{usingle\,(unreinforced)}$-Ultimate bearing capacity of the same isolated footing on unreinforced soil.

According to Lavasan and Ghazavi (2012), at the ultimate load, settlement of footing increased by the interference and reinforcement. The closely spaced footings tilt under vertical centric loads; this effect can be decreased by increasing the number of reinforcement layers. it is seen that reinforcing soil causes a significant decrease in the magnitude of the footing tilt.

Noorzad and Manavirad (2014) presented the effect of geotextile inclusion on the bearing capacity of two closely spaced strip footing located at the surface of soft clay using finite element analysis carried out in PLAXIS 2D. With a rising number of reinforcement layers, the bearing ability was found to increase if the reinforcement was placed within a range of effective depths. They indicated that increasing reinforcement stiffness beyond a threshold value does not result in a further increase in the bearing capacity. Compared to the unreinforced foundation, the reinforced foundation with two interfering strip footings, the failure zone tended to become wider and deeper than that for the unreinforced foundation.

Das and Samadhiya (2015) attempted to find out the effect of prestressing on unreinforced, geogrid reinforced and adjacency of square footings numerically. The bearing pressure improved by 300 to 500 % with respect to unreinforced soil, whereas it improved by about 200% with respect to geogrid reinforced soil. The improvement factor showed a decreasing trend with an increase in settlement. In the case of closely spaced footings prestressing improved 67% than unreinforced and almost 25% with respect to geogrid reinforced soil.

Lavasan et al. (2017) numerically examined the bearing capacity, settlement, and failure kinematics of two closely spaced circular footings on reinforced soil by a number of large-scale tests. Results indicated that the ultimate bearing capacity increases up to a maximum of 40 and 90% by the use of one and two layers of geogrid, respectively.

2.2.4. Settlement

Amer and Romi (1993) developed an approach to study the settlement and tilt of two interfering footings using non-liner constitutive laws of soils. They also developed non-dimensional correlations to compute maximum settlement and minimum settlement of the interfering footings.

Kumar (1997) stated that the magnitude of settlement and tilt decreases for a given load intensity in the case of interfering footings resting on reinforced soil, compared to the same footings on unreinforced soil for the same load intensity.

Nainegali and Basudhar (2011) developed a MATLAB code for the finite element modelling of two closely spaced footings resting on linearly elastic foundation soil whose modulus of elasticity is either constant or linearly varying with depth. From the study, it was concluded that Poisson's ratio does not have much influence on interference. Settlement increased with a decrease in spacing between footings and decreased with an increase in slope angle of linearly varying soil modulus with depth.

According to Lavasan and Ghazavi (2012), at the ultimate load, settlement of footing was found to be increased by interference. The failure in the reinforced soil foundation occurred at greater values of settlements, it may be concluded that the flexibility of soil is increased by an increase in the number of reinforcements. This means the soil can bear more pressure and settlement without reaching the failure limit.

Lavasan et al. (2017) examined the bearing capacity, settlement, and failure kinematics of two closely spaced circular footings on reinforced soil. Beyond the bearing capacity, the settlement of adjacent circular footings increases up to 45% compared with a single footing with the same safety factor.

Nainegali and Ekbote (2019) studied the behaviour of two closely spaced strip footings resting on the surface of the semi-infinite clay soil medium. Compared to that of the isolated footing, the settlement is found to increase. The effect of interference is noticeable for the bearing pressure and the settlement measured in the allowable range.

2.2.5. Tilt of the Footings

The estimation of bearing capacity and tilt were done from the pressure-settlement characteristics of the foundation soil by Verma (1986). Amer and Romi (1993) concluded that tilt is affected by a spacing ratio (S/B). Therefore, proportioning of interfering factors should be carried by actual estimation of settlement and tilt. Kumar and Saran (2003) observed that by providing continuous reinforcement layers in the foundation soil under the closely spaced strip footings, bearing capacity, settlement and tilt were considerably improved. According to Lavasan and Ghazavi (2012), by increasing the number of geogrid layers, the closely spaced footing tilt was decreased. Salamatpoor et al. (2019) studied the bearing capacity, and uneven settlement of consecutively constructed adjacent footings rested on saturated sand using model tests. It was observed that the interference of two adjacent footings (old and new) increased the settlement and tilt of older footing. It was also found that changing the safety factor of the old footing from 2 to 3 has a negligible effect on the tilting of the two interfering footings (less than 10%). Nainegali and Ekbote (2019) studied the behaviour of two closely spaced strip footings resting on the surface of the semi-infinite clay soil medium. A significant tilt occurred for the footings placed close to each other.

2.2.6. Multiple Closely Spaced Footings

Suppiah (1981) studied the interference of three parallel strip surface footings on silica sand. The tests were conducted with all the footings subjected to equal loads and with the two outer footings subjected to 50% and 75% of the middle footing loads. From the study, it concluded that the experimental efficiencies for interfering rough and smooth footings increase as spacing decrease and they reach a maximum value at a spacing ratio of 1.7. For closer spacing, higher efficiencies were obtained for rough footings than for smooth footings.

For the problem of three closely spaced strip footings on the sand, Graham et al. (1984) has used the stress characteristics to calculate the bearing capacity. Efficiency 'η_f' is the ratio of failure load of the central interfering footing to the capacity of similar isolated footing. Efficiencies are highest at close spacing and decrease until the footings behave independently.

Kouzer and Kumar (2008) obtained the interference effect due to a number of strip footings. The failure mechanism in this approach was chosen symmetrical about the centre line for any footing.

The interference effect on the vertical load-deformation behaviour of a number of equally spaced strip footings on dry sand was investigated by Kumar and Bhoi (2008). A new experimental set-up was proposed by them in which only one footing needs to be employed rather than the number of footings (Figure 2.4). Soil friction angle also played a prominent role in interference effect. The results of the experiments revealed that the bearing capacity increases continuously with a decrease in spacing among the footings.

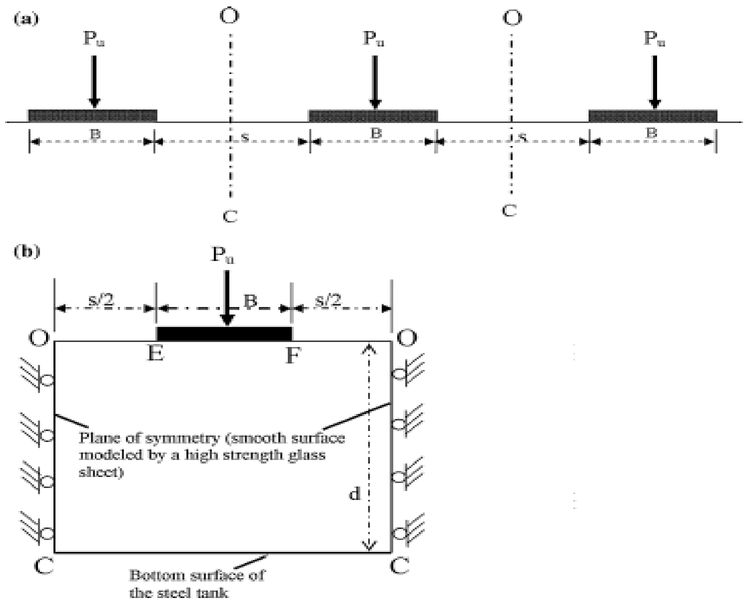


Figure 2.4. (a) Definition of problem; and (b) chosen boundary domain for experimental set up (Kumar and Bhoi, 2008)

Lee and Eun (2009) addressed the interference effect of multiple footings placed on the sand on the bearing capacity using field plate load tests and finite element analysis. It was observed that the load responses of multiple footings are similar to those of the single footing at distances greater than three times the footing width.

Kumar and Bhattacharya (2010) examined the ultimate bearing capacity of a number of evenly spaced multiple strip footings, equally loaded to failure at the same time by lower bound finite elements limit analysis. The efficiency factor is computed with respect to changes in the clear spacing between the footings. The ultimate bearing capacity of a group of footings and the isolated footing becomes equal when the S/B value more than or equal to 3. For a particular S/B value efficiency factor was more for rough footings as compared to smooth footings.

Kumar and Bhoi (2010) examined and compared the interference effect of multiple footings and strip anchors. The interference effect is more predominant in multiple footings or strip anchors compared to two adjacent footing/strip anchor case.

Daud (2012) studied the effects of multiple strip footing configurations on the bearing capacity were investigated by using nonlinear finite element analysis. Two and three-strip footings resting on the sand were analysed. The finite element analyses were used to quantify the multiple-footing effects on the bearing capacity ratio. Under the in-contact condition, the values of the bearing capacity ratio were observed to be smaller than what would be obtained from the conventional bearing capacity equation due to the size effect. Also, a method to estimate the bearing capacity ratio for the different multiple strip footing configurations was derived.

Yang et al. (2017) investigated the ultimate bearing capacity factor (N_γ) and failure mechanisms of multiple rough strip footings with equally spacing placed on sand using the upper-bound finite element method. The obtained failure mechanisms are predominantly composed of mesh like rigid blocks and a fully curved trapped wedge below the base of the footing.

2.3. INTERFERENCE EFFECTS OF CLOSELY SPACED FOOTINGS ON LAYERED SOIL

2.3.1. Isolated Footing on Layered Soil

Early methods for calculating the bearing capacity of footings on sand over clay, can be broadly classified as either the projected area model of Terzaghi and Peck (1948) or the punching shear model of Meyerhof (1974). Terzaghi and Peck's (1948) projected area model is a load spreading model and is based on the assumption that the top sand layer distributes the pressure q_u applied on its surface uniformly to a hypothetical equivalent footing with width, B resting on the top of the clay. The capacity of the layered system is thus assumed to equal the bearing capacity of a footing with width B on the surface of the clay. This model of Terzaghi and Peck (1948) attempts to calculate the bearing capacity of a strong layer, overlying a weak layer. They assumed that the top layer served mainly to spread the footing load to a large area on the lower layer surface, hence reducing its intensity. The bearing capacity of a surface footing is given by,

$$q_u = q_c[1 + 2(H/B)tan\,\alpha] \le q_s \tag{2.3}$$

where q_u-Ultimate bearing capacity, q_c-Ultimate bearing capacity of clay, q_s-Ultimate bearing capacity of the sand layer, H-Thickness of upper layer, B-Width of footing, α-Load spread angle

A different approach, based on experimental studies, was proposed by Meyerhof (1974) and it describes the footing as a rigid slab, punching the block of sand immediately below it downwards into the clay. Hence, this model is known as the punching shear model (Figure 2.5). The punching shear mechanism provides the bearing capacity as the sum of the shear resistance developing along the assumed vertical failure planes in the sand, and of the bearing capacity of a footing embedded in the bottom clay layer. For surface strip footings on layered soil, (dense sand on soft clay) the ultimate bearing capacity as defined by Meyerhof and Hanna (1978) is expressed in Equation 2.4.

$$q_u = cN_c + \Upsilon_{sand}\, H^2 K_s \frac{\tan \Phi_{sand}}{B} \leq \frac{1}{2}\Upsilon_{sand}\, BN_{\Upsilon} \qquad (2.4)$$

In which c- Undrained cohesion of clay, Nc=5.14, Nc and Nγ Bearing capacity factors, B- Width of footing, Υ_{sand}- Unit weight of sand, Ks- Punching shear coefficient, H-Thickness of top sand bed, ϕ_{sand}-Angle of internal friction of sand.

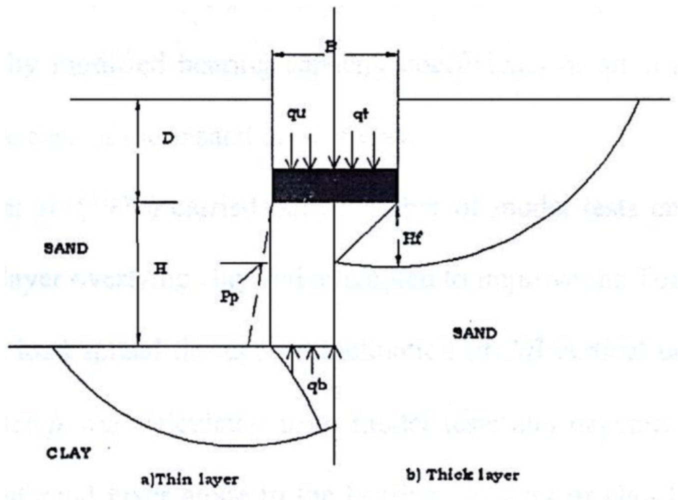


Figure 2.5. Bearing capacity analysis for sand overlying clay (Meyerhof, 1974)

Shivashankar et al. (1993) studied the improvement in the bearing capacity of footings resting on granular bed overlying soft clay, assuming a punching shear failure mechanism in the foundation soil. Both the footing and the section of the reinforced granular bed immediately below the footing are envisaged to act in tandem to punch through the soft soil below in the proposed punching shear failure mechanism. The total shearing stresses along the vertical planes through the edges of the footing in the upper layer, both due to the shear layer and confinement effects are assumed to get redistributed as additional exponentially varying surcharge stresses onto the lower soft clay layer on either side of the footing. This surcharge effect also contributes to the increase in the bearing capacity. The improvement in bearing capacity of a reinforced granular bed is attributed to three effects: Shear layer effect, Confinement effect and Surcharge effect. The ultimate bearing capacity of a footing resting on granular bed overlying soft soil is given by

$$q_u = c_u Nc + \frac{K_p \gamma_s H^2 \tan \phi_s}{B} + \frac{2T_R \, tan\phi_S}{B} + 0.84(\Delta q_{SL} + \Delta q_{CE}) \qquad (2.5)$$

where kp-Coefficient of passive lateral earth pressure, T_R-Reinforcement force, ϕ_R-friction angle between the reinforcement and granular soil, Δq_{SL}-Increase in bearing capacity due to shear layer effect, Δq_{CE}-Increase in bearing capacity due to confinement effect.

The improvement in bearing capacity, defined in terms of bearing capacity ratio, BCR as the ratio of improved bearing capacity to the original bearing capacity is given as

$$BCR = 1 + \Delta BCR_{SL} + \Delta BCR_{CE} + \Delta BCR_{SE} \qquad (2.6)$$

where ΔBCR_{SL}, ΔBCR_{CE} and ΔBCR_{SE} are improvements in bearing capacity ratio due to the shear layer effect, confinement effect and additional surcharge effect, respectively (Shivakumar Babu 2009).

Rethaliya and Verma (2009) conducted experimental and mathematical modelling on strip, rectangular and square footings on reinforced sand layer overlying soft clay. The optimum thickness of the sand layer is much higher in the unreinforced case compared to 0.8 times the width of footing in the reinforced case.

Kumar and Chakraborty (2015) studied the bearing capacity of a circular footing on clay overlying sand layer by lower bound limit analysis with finite elements and linear optimisation. A non-dimensional efficiency factor (η) which is defined as the ratio of bearing capacity in the presence of sand layer, to that for a footing placed directly over clayey strata was calculated. The efficiency factors increase with an increase in ϕ and $\frac{q}{\gamma b}$ and a decrease in $\frac{c_u}{\gamma b}$. The pattern of failure shows that the inclusion of the sand layer below the base usually contributes to a wider expansion of the plastic field. The dispersion angle is similar to the study of the dilation angle prescribed.

Based on centrifuge experiments on dense sand overlying clay, it was found that with both the strength of the clay and the overburden pressure at the base of the footing, bearing capacity increases linearly (Okamura et al. 1997). Okamura et al. (1997,1998) expanded the punching shear model of Meyerhof (1974) considering the inclined failure planes on sand based on experimental tests with sand.

Saha Roy and Deb (2017) conducted experimental tests on rectangular footings on unreinforced or reinforced sand overlying soft soil. An analytical model was proposed to calculate bearing capacity. Results of model plate load tests of rectangular footings of various aspect ratios resting on unreinforced or reinforced sand overlying soft soil were presented.

Salimi et al. (2018) attempted to estimate the undrained bearing capacity of a strip footing resting on the surface of a finite thick sand layer overlying clay, using finite element limit analysis. A new simple bearing capacity model, which captures the variation in shear resistance from the sand layer with the dimensionless undrained strength of the clay layer was proposed.

Using finite element limit analysis, Yang et al. (2020) calculated the bearing capacity of ring foundations resting on a sand layer overlying clay. According to Yang et al. (2020), punching shear failure occurred in the sand layer for $H/R_0 < Hc/R_0$, (H-Thickness of sand layer, R_0-External radius) with log-spiral rupture lines extending from the clayey strata to the upper sand layer.

Kumar and Chakraborthy (2020) computed the bearing capacity of the strip and circular footings resting on two-layered clays. The strength of the bottom clay layer did not affect beyond a certain top clay layer thickness (t_{opt}). The topt/b value was found to vary depending on the foundation type and c_{u1}/c_{u2} ratio (where t_{opt}-Optimum top layer thickness, b- Diameter/width of foundation, c_{u1} and c_{u2} are undrained cohesion values of the top and bottom clay layers respectively).

Studies by Panwar and Dutta (2020) found that the ultimate bearing capacity increased up to a H/W value of 1.75, and beyond this value of H/W of 1.75 the increase was only marginal. They studied rectangular footings on the upper dense sand layer overlying loose sand layer.

2.3.2. Closely Spaced Footings on Layered Soil

Das et al. (1993) conducted experimental studies with closely spaced footings on dense sand overlying soft clay. Ultimate bearing capacity was found to increase with an increase in the thickness of dense sand up to critical depth H_{cr} after which it was found to remain constant.

Ghosh and Sharma (2010) studied the settlement behaviour of two strip footings placed in close spacing on layered soil deposit consisting of a strong top layer underlying a weak bottom layer. The finite difference method was used to solve the differential equations which are derived from the theory of elasticity. They concluded that settlement reduces as the spacing between the footings increased and eventually reaches the same value as that of an isolated footing free from interference-effect. The study found that by improving the properties of the weak bottom layer, settlement beneath interfering footings can be reduced.

Ghosh and Kumar (2011) studied the interference effects of strip footings on cohesionless layered soil through model tests. The bearing capacity of adjacent footings was found to reach a maximum at a specific critical spacing between the footings. The same type of soil with different relative density and angle of friction were considered in different layers, in which the weak layer was overlying the strong layer. The authors concluded that the bearing capacity of single footing on the layered deposit decreases with an increase in D/B where D is the depth of the top weak layer, and B is the width of footing respectively. Variation of efficiency factor due to bearing capacity and due to settlement followed the same trend but different in magnitude. They found that the critical value of the spacing ratio, S/B at which efficiency factor due to bearing capacity becomes the maximum is not a fixed one, which could even happen at a further lower or higher value of S/B.

Srinivasan and Ghosh (2013) conducted experimental studies on circular and rectangular footings on cohesionless layered soil. The study shows that irrespective of the type of deposit, the ultimate bearing capacity of interfering footing increased with the decrease in the spacing between the footings. The settlement also followed the same trend as that of bearing capacity. With an increase in depth of the weak upper layer, in a double layer soil bed, the ultimate bearing capacity and settlement decreased.

On two closely spaced square and rectangular footings, each of two different sizes and sitting on the surface of a two-layered sand deposit, Ghosh et al. (2015) performed experimental work. They found that the bearing capacity and settlement values of the closely spaced footings on the layered deposit decreased with the rise in the D / B ratio. Efficiency and settlement factors were presented with respect to S/B values. The effects of interference of the footings on their bearing capacity and settlement behaviour compared to those of a single isolated footing are presented in terms of efficiency and settlement factors respectively. The efficiency factors were found to be maximum at S/B=0.5.

Saha Roy and Deb (2019) studied the interference effects of bearing capacity and settlement of angular footings (square and rectangular) resting on granular fill over soft clay through model tests. The optimum spacing ratio was obtained as 1.5 times the width of footing, and it was found to be independent of the aspect ratio of footings. Their analytical solution provides the bearing capacity as the sum of bearing capacity contribution due to passive earth pressure developed at the sides of the sand block and the bearing capacity due to the load spread mechanism.

Using an upper-bound limit state plasticity method known as discontinuity layout optimization, Zheng et al. (2021) calculated the ultimate bearing capacity of two interfering strip footings on sand overlying clay. The ultimate bearing capacity of two interacting strip footings on sand overlying clay is found to be affected by geometric patterns and soil characteristics. Increasing the angle of internal friction or decreasing $c_u/(\gamma B)$ was found to increase the value of critical spacing.

2.4. EFFECT OF FORMATION OF VOID

The effect of the presence of void on bearing capacity of shallow footing has been studied experimentally and numerically. Baus and Wang (1983) studied the bearing capacity behaviour of strip footing over a continuous void. There is a critical depth below which the void's existence has a minimal impact on the output of the foundation. When the void is located above the critical depth, the bearing capacity of the footing varies with various parameters, such as the size and location of the void and the depth of foundation.

By using a three-dimensional finite element computer programme, Wang and Badie (1985) investigated the impact of underground void on the stability of shallow foundation supported by a compacted clay. The authors concluded that there exists a critical depth, and only when the underground void is located above the critical depth will it affect the stability of the footing. Since the critical depth varies with many factors including footing shape, void shape, void orientation, void size, and soil type, further research is needed to establish the relationship between these influencing factors and the critical depth. Such a relationship is vital in the development of a design procedure to assure the stability of a shallow foundation founded above a void.

Wang and Hsieh (1987) developed a rational method for footing stability analysis using the upper bound theorem of limit analysis for strip footing centred above a continuous void. Equations connecting collapse footing pressure with the soil strength property and the size and location of the void were developed. Azam et al. (1991) evaluated the performance of a strip footing on a homogeneous soil and two-layered stratified soil both with and without void. Performance analyses were done by the two-dimensional finite element method. Significant outcomes from this study were that the soil layer of finite thickness underlain by bedrock would have negligible influence if the soil thickness approaches approximately six times footing width. For a two-layer soil system, top layer thickness and strength ratio between the two layers affect the footing performance. The degree of influence of void on footing performance was found to depend on void location, depth to bedrock, layer thickness and strength ratio.

By finite-element method analysis, Kiyosumi et al. (2007) have numerically investigated the impact of multiple voids on the yielding pressure of strip footing. The findings showed that the failure zone formed exclusively from the base towards the nearest void and did not necessarily extend to the other voids. The failure zone was smaller and narrower than that of the no-void soil, resulting in lower-yielding pressure. For the estimation of the yielding pressure of strip footing above multiple voids, a practical calculation formula was established.

Analyses of bearing capacity of strip footing on the stiff ground with voids were done through model tests by Kiyosumi et al. (2011). Different failure modes are disclosed based on experimental analyses. Depending on the position as well as the size of the voids, three kinds of failure modes for a single void were known, such as bearing failure without void failure, bearing failure with void failure and void failure without bearing failure.

Lavasan et al. (2016) numerically studied the bearing capacity and failure mechanism of strip footings over twin voids. Results demonstrated that there would be a critical depth for voids and a critical distance between them. The mode of failure depends on the size and location of the voids as well as that of the footing.

2.5. GAPS IN LITERATURE

- The interference effect on shallow footings first noticed in 1962 by Stuart. Later on, many researchers focused on the interference effect on shallow footings. Most of the available studies are focused on homogeneous soils, especially cohesionless soils.
- Most of the previous interference studies considered the loading condition in which both the adjacent footings loaded simultaneously. But in actual conditions sequential loading cases are common.
- In many practical situations in the field, granular beds are placed on the weak soil to improve the strength characteristics of the soil. A few researchers have

studied interference effects on layered soils. Studies on the layered soil system are mainly conducted on the sand. Interference effects on strong sand overlying weak soil are not much addressed.

- In many situations, void spaces could be formed in weak soil strata. The presence of void could adversely affect the bearing capacity of the soil, and ultimately, it leads to the failure of the structure. The presence of voids under the isolated footing is mainly considered in previous studies. Performance of adjacent footings overlying weak soil which contains voids are not much focused.
- Most previous studies in the literature which studied interference effects of adjacent strip footings on granular bed overlying weak soil have not provided an analytical model. This research work attempted to provide an analytical model to estimate the ultimate bearing capacity of two and three adjacent strip footings resting on granular bed overlying weak soil, with a fair and acceptable degree of accuracy.

CHAPTER 3

METHODOLOGY

3.1. GENERAL

To study the interference effect between closely spaced adjacent strip footings on the surface of granular soil, and their behaviour, both numerical and experimental investigations are conducted in this research work. Mainly numerical analyses and a few experimental studies are carried out for adjacent strip footings placed on granular soil and layered soils. The summary of experimental and numerical studies carried out on adjacent strip footings are shown in Table 3.1. The methodology adopted in this study is shown in a flowchart (Figure 3.1). Mostly two adjacent strip footings are being studied. Three footings are studied in the case of footings on granular soil. Effect of reinforcing the granular soil and presence of void/s in the weak soil are also considered.

3.2. EXPERIMENTAL AND NUMERICAL INTERFERENCE STUDIES OF ADJACENT STRIP FOOTINGS ON UNREINFORCED AND REINFORCED MEDIUM DENSE SANDS

In the experimental study, a series of laboratory-scale plate load tests are conducted to study the interference effect of two closely spaced strip footings on medium dense river sand which are loaded simultaneously. The results are addressed regarding bearing capacity and settlement of the footings. The experimental results are complemented with numerical analyses in the case of simultaneous loading case. The spacing between the footings, width of the footings, number of reinforcement layers are the parameters that are varied in this study. The details of the experimental setup, test methodology, materials used, and parameters studied are explained in the following sections.

Table 3.1. Summary of studies on adjacent strip footings

Sl. No.	Description of soil bed	Type of analysis		No. of footings*		Type of Loading		Presence of void		Type of Reinforcement	
		Experimental	Numerical	Two	Three	Sim[1]	Seq[2]	with	without	Continuous	Discontinuous
1	Unreinforced granular soil without void	√	-	√	-	√	-	-	√	-	-
		-	√	√	-	√	√	-	√	-	-
		-	√	-	√	√	-	-	√	-	-
2	Reinforced granular soil without void	√	-	√	-	√	-	-	√	√	-
		-	√	√	-	√	-	-	√	√	-
		-	√	√	-	-	√	-	-	-	√
3	Unreinforced granular bed (GB) on clay without void	-	√	√	-	√	-	-	√	-	-
		-	√	√	-	-	√	-	√	-	-
4	Unreinforced granular bed (GB) on clay with void	-	√	√	-	√	-	√	-	-	-
		-	√	√	-	-	√	√	-	-	-
5	Reinforced granular bed (RGB) on clay without void	-	√	√	-	√	-	-	√	√	-
		-	√	√	-	√	-	-	√	-	√
6	Reinforced granular bed (RGB) on clay with void	-	√	√	-	√	-	√	-	√	-
		-	√	√	-	√	-	√	-	-	√

*In each of (1-6) cases, single footings on surface of soil are also studied for reference; 1 Simultaneous loading; 2 Sequential loading

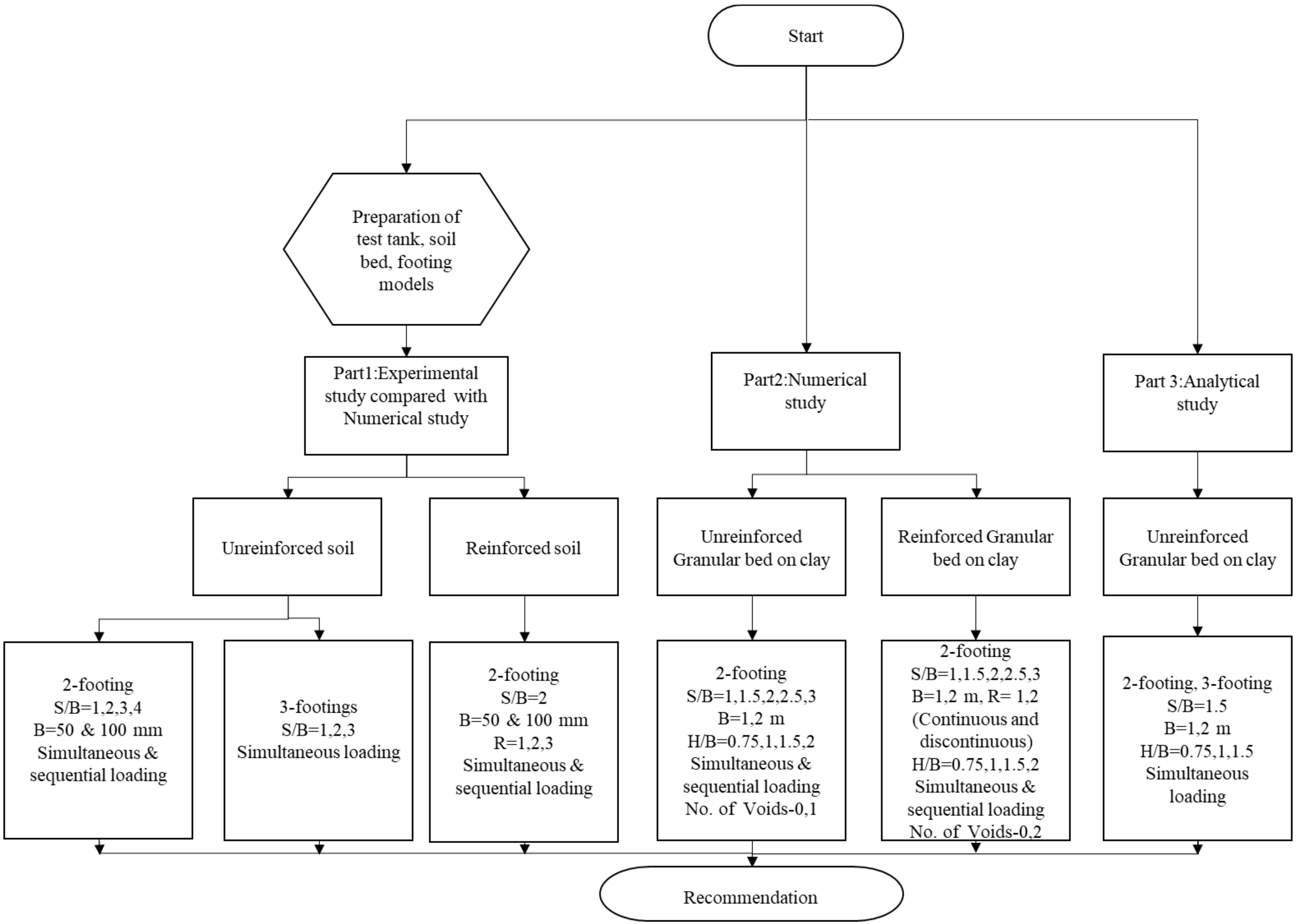


Figure 3.1. Flowchart of Methodology

3.2.1. Experimental Study

3.2.1.1. Materials Used

Medium dense sand is used as the foundation material for the model tests. The particle size distribution curve is illustrated in figure 3.2. The sand was used in the dry condition in all the tests. As per IS 1498 (1970), the sand will classify as poorly graded sand (SP). Properties of the sand as determined from laboratory tests are shown in Table 3.2. Shear strength parameters are obtained from shear box tests. Both unreinforced and reinforced sands are considered in the experimental study. The reinforcements, in the case of the reinforced sand bed, were provided in the form of a hexagonal wire mesh with a wire diameter of 0.5 mm and aperture of mesh 20 mm x 20 mm, as shown in figure 3.3. The wire mesh is very flexible and double twisted. The reinforcements are provided in one, two or three layers during laboratory-scale plate load tests. The tensile strength of reinforcement was determined to be 40 kN/m.

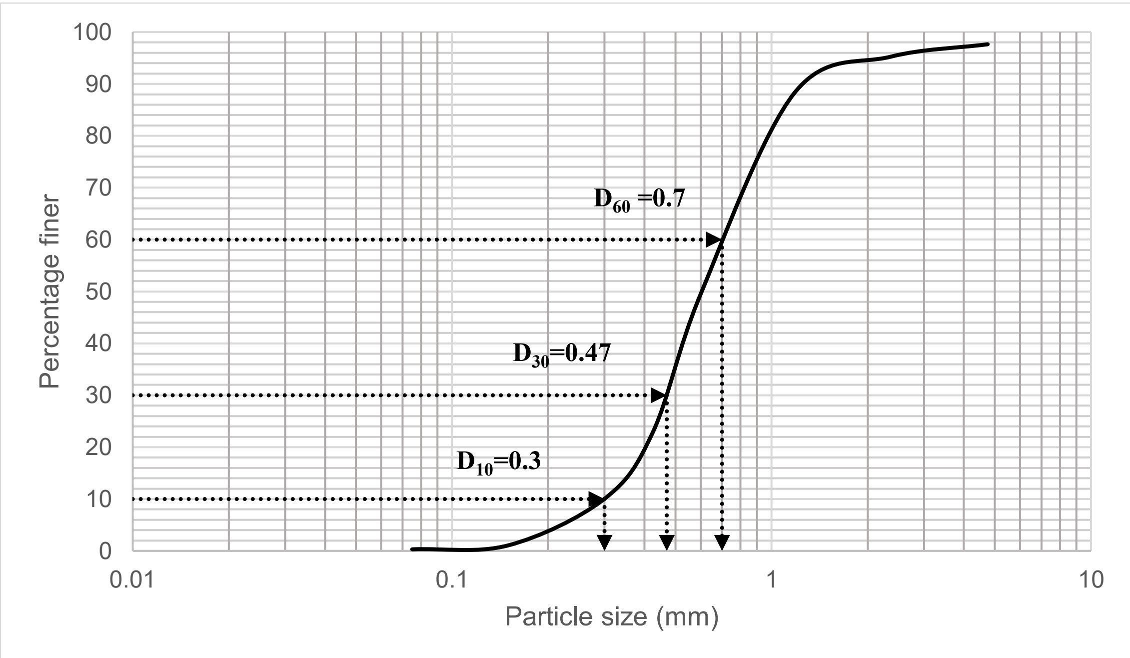


Figure 3.2. Particle size distribution curve of sand used in experimental work

Table 3.2. Properties of sand used in model tests

Particulars	Value
Specific gravity	2.63
Effective grain size D_{10} (mm)	0.30
Coefficient of uniformity, C_u	2.33
Coefficient of curvature, C_c	1.05
Maximum dry density of soil (kN/m^3)	19.70
Minimum dry density of soil (kN/m^3)	15.30
Angle of friction (φ) (Degree)	36
Cohesion, c (kPa)	0.01
Relative density (%)	75
Soil classification	Poorly graded sand (SP)

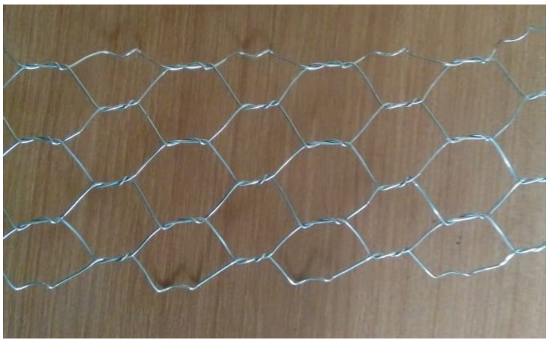


Figure 3.3. Hexagonal wire mesh used for reinforcing the soil

3.2.1.2. Experimental Programme

The tests are conducted in a rectangular ferrocement tank of size 1.18 m x 0.91 m x 0.65 m, with care taken to minimise the boundary effects. Firstly, laboratory-scale plate load tests were conducted for a single independent strip footing resting on sand (widths 50mm and 100mm) (Figure 3.4a). Also, the tests were performed, with a single strip footing, on reinforced soil with reinforcement placed in one layer, two layers or three layers in the different tests. The reinforcements are placed at B/2 depth from the top of the soil bed in case of one layer, at B/3 depth in case of two layers and B/4 depth in case of three layers of reinforcement. The length of the reinforcement was such that the reinforcement extends a 'B' distance from either edge of the strip footing laterally (Figures 3.4b-d).

The load tests were next performed on two footings. Two footings of a set are placed on cohesionless soil with no reinforcement. Both the footings are loaded simultaneously until failure (Figure 3.5a). Each of the two footings was considered to carry the same ultimate failure load, P_u due to symmetry. Spacing between the footings 'S' is varied from 1B to 4B in both experimental and numerical studies for 50 mm wide footing. Spacing between the footings 'S' is varied from 1B to 3B in both experimental and numerical studies for 100 mm wide footing. The tests with reinforced soil conditions are conducted with spacing between two strip footings kept as 2B. The spacing 2B was selected in tests with reinforced soil because S=2B showed a maximum effect of interference in the unreinforced cases. Figure 3.5 show tests conducted with two strip footings on the sand with and without reinforcement.

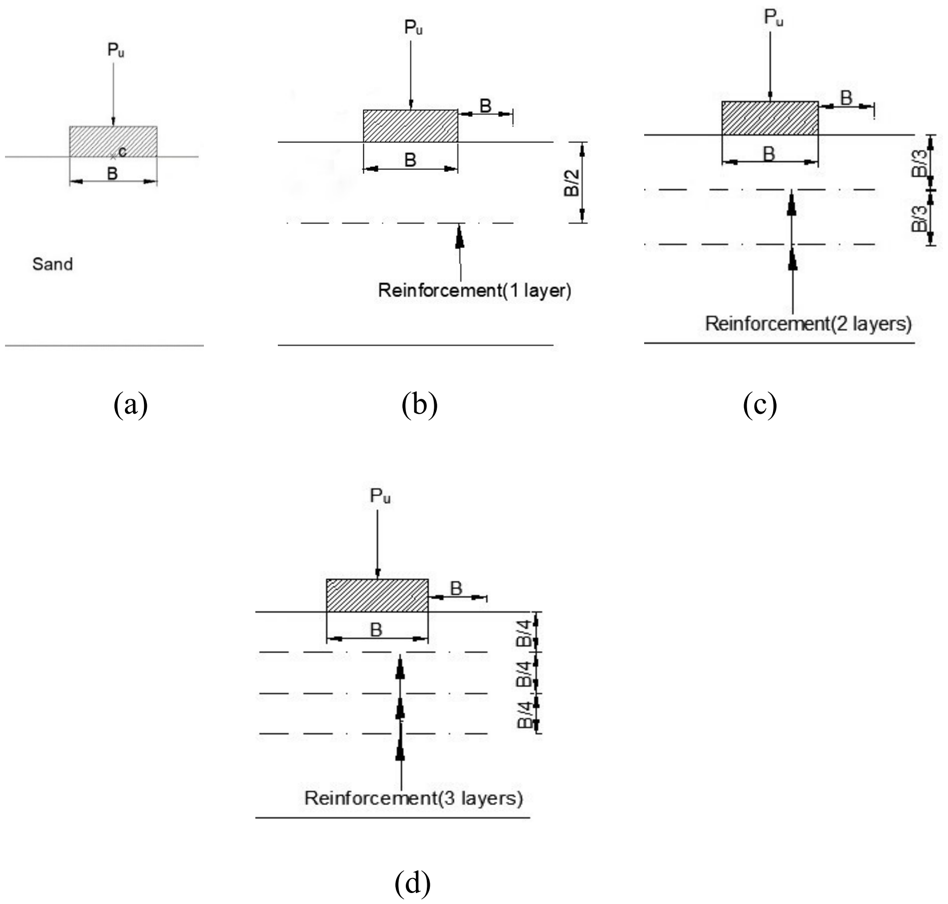


Figure 3.4. Laboratory tests performed on single strip footing (a) Without reinforcement, (b) With reinforcement-1 layer, (c) With reinforcement-2 layers, (d) With reinforcement-3 layers

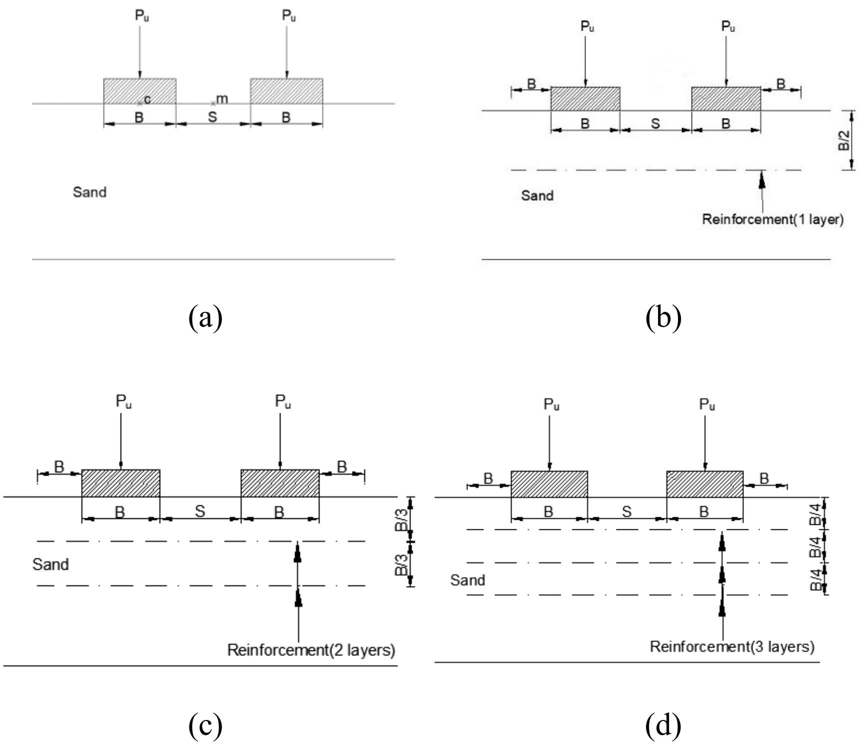


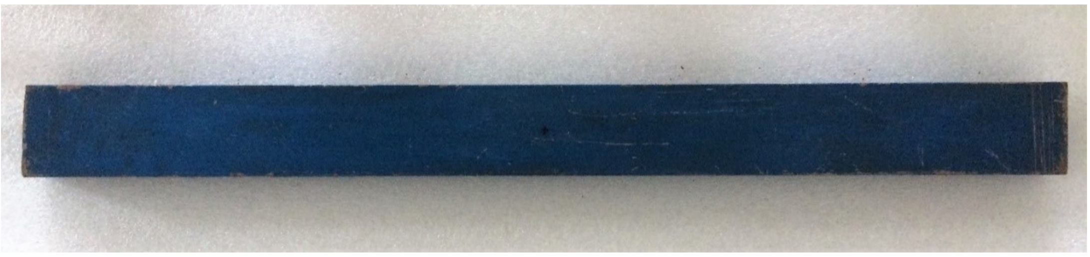
Figure 3.5. Laboratory tests performed on two strip footings (a) Without reinforcement (S=1B to 4B), (b) With reinforcement-1 layer (S=2B), (c) With reinforcement-2 layers (S=2B), (d) With reinforcement-3 layers (S=2B)

3.2.1.3. Experimental Procedure

A rigid and strong loading frame is used, and vertical loads are applied on the two footings, through a connecting beam, and the applied loads were measured using load measuring devices. Two dial gauges are attached to each of the footings in order to measure the vertical displacement of the footing. The average of the settlement values obtained from two dial gauges installed on each footing is considered as vertical settlement of the footing. The strip footing models with dimensions 305 x 100 x 25 mm thick and 305 x 50 x 25 mm thick are made of seasoned wood. 12 mm thick steel plates are having the same plan dimensions as the model footings are placed on top of wooden footings. A steel shaft having a diameter of 19 mm is rigidly attached to each model footing at its centre (Figure 3.6). In the case of studying a single strip footing, the load is directly applied onto the steel shaft without the connecting beam. In the case of interference study between two footings, a horizontal steel bar (connecting beam) having a cross-section of 50.8 mm x 25.4 mm connects the steel shafts (Figure 3.7).

The load is applied at the centre of the horizontal bar, which then distributes the load equally to the two footings. The load is applied gradually at a constant strain rate of about 0.1 mm/min on the footings. Due to the rigid nature of the loading frame, rotation/tilt of footings are restrained in the experimental study. The sides of the tank are provided with a polythene sheet to reduce the effect of side friction. The soil used in this study is river sand. Bottom layers in the testing tank placed 10 cm layer-wise and compacted manually using a mini rammer. The upper half of the sand bed was prepared using the sand raining technique, keeping the height of fall as 150mm in order to maintain constant relative density (75%). After placing the sand up to the required level, the sand surface is levelled, using a spirit level. The schematic diagram of the experimental setup is shown in figure 3.8. A photographic view of the experimental setup is shown in figure 3.9. The testing programme is shown tabulated in Table 3.3.

Figure 3.6. Two sets of footings of width 50mm each and 100mm each



(a) Top view

(b) Bottom view

Figure 3.7. Horizontal bar (Connecting beam) used in the experimental setup

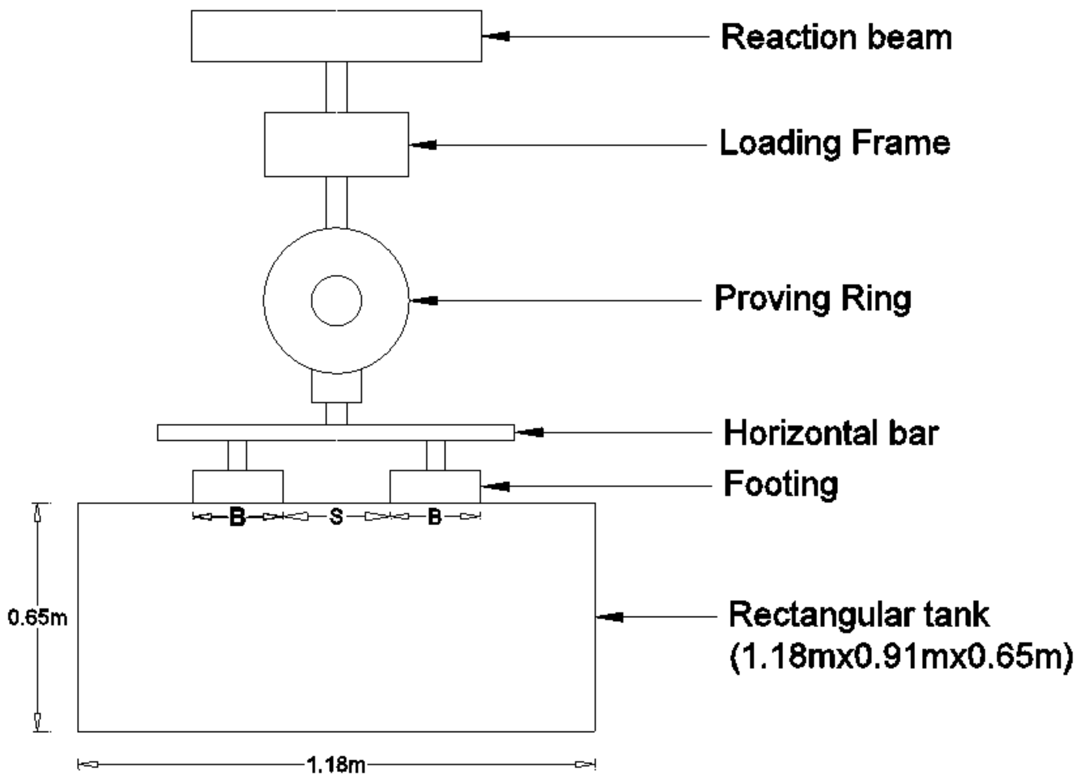


Figure 3.8. Schematic diagram of the experimental setup

Figure 3.9. Photographic view of the experimental setup

Table 3.3. Testing programme

	Footing width (mm)	S/B Ratio	Number of reinforcement layers
Single footing	50	Single, independent	0,1,2,3
	100	Single, independent	0,1,2,3
Two footings	50	1	0
	50	2	0,1,2,3
	50	3	0
	50	4	0
	100	1	0
	100	2	0,1,2,3
	100	3	0

3.2.2. Numerical Study

Numerical analysis is conducted by using the finite element-based program PLAXIS 2D. For different kinds of geotechnical applications, PLAXIS is intended to conduct deformation and stability analysis. Either a plane strain or an axisymmetric model may model real circumstances. The software uses a convenient graphical user interface that allows users to create a geometry model and finite element mesh based on a representative vertical cross-section of the situations at hand. The simple graphical input processes allow complex finite element models to be generated quickly, and the improved output facilities provide a detailed presentation of computational results. The calculation is fully automated and based on robust numerical procedures. The models produced by PLAXIS can be considered as a qualitative representation of soil behaviour.

3.2.2.1. Interference Studies of Adjacent Strip Footings on Unreinforced and Reinforced Medium Dense Sands

A series of laboratory-scale plate load tests are conducted to study the interference effect of two closely spaced strip footings on medium dense river sand which are loaded simultaneously. The experimental results are complemented with numerical analyses. In this study, PLAXIS 2D, a finite element program was used to simulate the interference of footings corresponding to the model studies carried out. The material properties of the soil and footing assigned are given in Table 3.4. Young's Modulus of sand in various tests is shown in Table 3.5. The strip footings similar to the experimental study are considered to be placed on the ground surface. The behaviour of soils is numerically simulated by the Mohr-Coulomb failure criterion, which is an elastic-perfectly plastic model. In most realistic cases, this robust and simple non-linear model is based on soil parameters that are known. The Mohr-Coulomb model, as well as other applications in which soil failure behaviour plays a dominant role, can be used to measure realistic bearing capacities and collapse loads of foundations. Plane strain condition and fifteen noded triangular elements with 12 Gauss stress points are used to represent the soil domain. The footings have been considered as rigid surface strip footings modelled for wood and represented by the linear elastic model. The reinforcement is modelled using geogrid elements while analysing cases of reinforced soil conditions, and the properties of the reinforcement used (hexagonal wire mesh) are assigned to it. The property assigned is axial stiffness (EA), which is obtained from the stress-strain relationship of the hexagonal wire mesh. The bottom boundary is restricted in all directions and vertical boundaries restricted in horizontal directions. A few trial analyses are conducted to investigate the mesh dependency of failure load. Generating finer mesh led to a satisfying result in the numerical analyses when compared with the experimental results.

Table 3.4. Material properties for numerical analyses

Properties	Sand	Footing
Material model	Mohr-Coulomb	Linear elastic
Material Type	Drained	Non-porous
Unit Weight, ϒ (kN/m^3)	18.36	-
Young's Modulus, E (kN/m^2)	Obtained from laboratory stress-strain graphs*	10×10^6
Poisson's ratio, ν	0.30	0.30
Cohesion, c (kN/m^2)	0.01	-
Angle of internal friction, Φ (°)	36	-
Interface reduction factor	0.80	-

Table 3.5. Young's Modulus of sand in various tests*

	B=50mm	B=100mm
Cases	Youngs modulus, E (kN/m^2)	
Single footing	567	2000
Single footing (R=1)	2800	2500
Single footing (R=2)	4000	8000
Single footing (R=3)	6250	10000
S/B=1	1333	3500
S/B=2	2000	3000
S/B=3	1500	3750
S/B=4	1000	3214
S/B=2(R=1)	6250	3500
S/B=2(R=2)	10000	15000
S/B=2(R=3)	16000	16667

The study is carried out by varying the spacings between the footings, i.e., for spacing ratio, S/B of 1, 2, 3 and 4 and single footing cases for 50mm and 100mm wide footing widths. Spacing between the footings 'S' is varied from 1B to 3B in both experimental and numerical studies for 100mm wide footing. 'S' is the clear spacing between the footings, and 'B' is the width of footing. The numerical study is done for two loading conditions. In the first loading condition, both the strip footings are loaded up to failure (Figures 3.10a-b). The first loading condition is compared with the experimental results. In the second loading condition, one of the strip footings representing an already existing foundation is loaded with half of the estimated failure load of single strip footing, and adjacent new strip footing loaded up to failure (Figures 3.11a-b). The study is done for both unreinforced (Figures 3.10 a, 3.11a) and reinforced soil conditions of the foundation soil (Figures 3.10b, 3.11b). In figure 3.11b, the reinforcement layers beneath the new footing extend equally beyond footing on either side and up to the property line, which is considered to be halfway between the two strip footings.

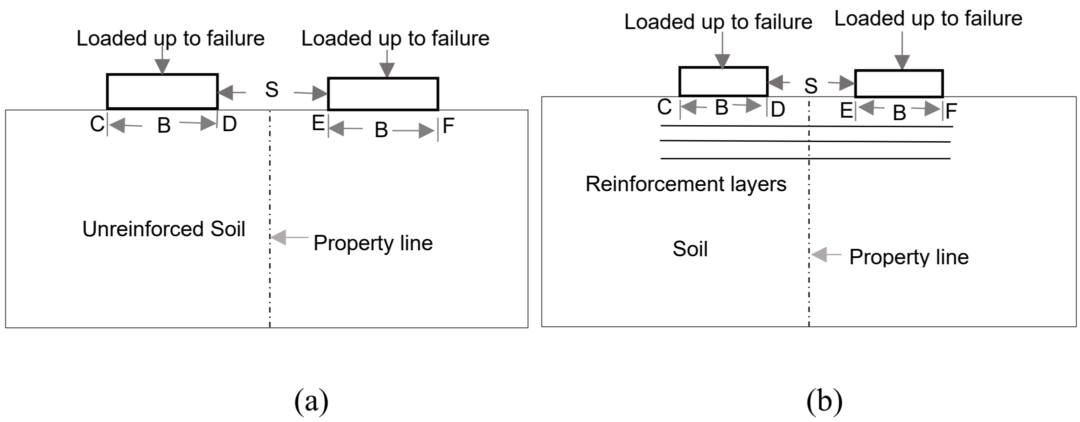
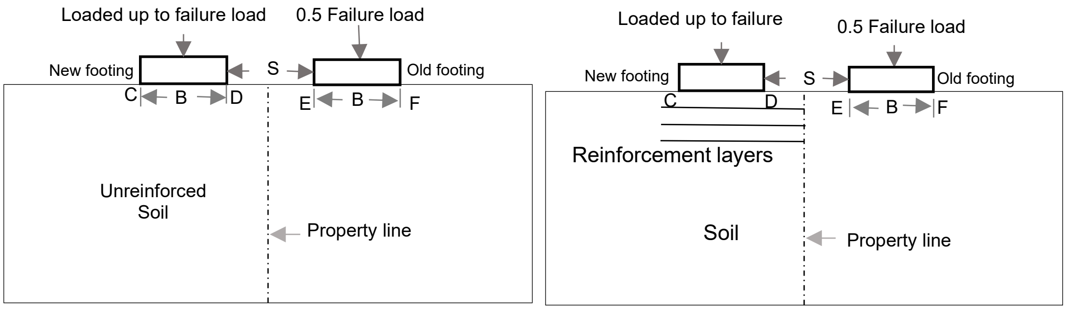


Figure 3.10. Numerical analyses performed on two strip footings loaded simultaneously on (a) unreinforced soil, and (b) reinforced soil



(a) (b)

Figure 3.11. Numerical analyses performed on two strip footings loaded sequentially on (a) unreinforced soil, (b) only new footing is placed on reinforced soil

i) Steps used to model the problem using PLAXIS 2D

One of the essential ingredients for successful finite element analysis of a geotechnical problem is the selection of a soil constitutive model. Since all aspects of real soil behaviour can not be replicated by any of the available soil constitutive models, it is important to determine which soil features regulate the behaviour of a specific geotechnical problem. The availability of suitable soil data from which to derive the required model parameters is another factor that governs the choice of a constitutive model. In the present study, the behaviour of soils is simulated by the Mohr-Coulomb failure criterion, which is an elastic perfectly plastic model. Since the study mainly focuses on bearing capacity, and all the parameters can be obtained from laboratory experiments, this model is sufficient. Plane strain condition and fifteen noded triangular elements with 12 Gauss stress points are used to represent the soil domain. Failure loads are generally overpredicted using 6-noded elements. It is a plane stain problem since the length of the footing is more compared to its width. A plane strain model is used for a certain length perpendicular to the cross-section (z-direction) for geometries with a uniform cross-section and corresponding stress state and loading scheme. Displacements and strains in the z-direction are assumed to be zero.

PLAXIS modelling procedure consists of 5 modes, and the modes are separated into geometry mode and calculation mode. Soil and structure are included in geometry mode where all the geometry, soil stratigraphy, water levels, structural elements and forces are defined. The calculation mode consists of mesh, flow conditions and staged construction. In all analyses, rigid surface strip footings are considered. Analyses are being performed under load control. The roughness of the footing was simulated by not considering the interface element at the footing-soil interface. The outer boundaries are of the same dimensions as the tank used for model tests. The inbuilt five noded geogrid elements are used as reinforcement with axial rigidity, EA. The interaction between the soil and reinforcement is simulated by providing an appropriate value for the strength reduction factor, R_{inter} at the interface. The modulus of elasticity values of soils is calculated from stress-strain graphs obtained from laboratory tests. The loads are applied using line loads.

When the geometry model is fully defined, geometry has to be divided into finite elements. A composition of finite element is called mesh. Mesh is generated in mesh mode. PLAXIS provides an automated mesh generation system. The generation of mesh is based on a robust triangulation procedure. A fine mesh is adopted in the study.

Finite element calculation can be divided into sequential calculation phases. Initial stresses in the soil are generated in the initial phase by the K_0 procedure, K_0 estimated by Jaky's equation ($K_0=1-\sin\phi$) (Jaky 1944). For performing an elastic-plastic deformation analysis, a plastic calculation is used. If the updated mesh parameter has not been selected, the calculation is performed according to the small deformation theory. In the case of reinforced soil structure updated mesh analysis is used where deformation is relatively small. In the analysis, the total load level is determined globally by means of the total load multipliers. To simulate the testing procedure in the model tests, a staged construction procedure is adopted. In the initial stage, initial stresses in the soil are generated. In the first phase, soil layer up to reinforcement is activated. In the second phase, geogrid is activated. In the third phase, soil above reinforcement is enabled. Footings are activated in the next stage, and in the later stage, line loading is simulated. PLAXIS has an automatic load stepping procedure for the solution of non-linear plasticity problems. The procedure terminates the calculation when the specified state or load level (ultimate state or ultimate level) is reached or when soil failure is detected. If at the end of the calculation, the defined state or load level has been reached, the calculation is considered to be successful. If the defined state or load level has not been reached, the calculation is considered to have failed. The load settlement curves and deformed mesh can be generated from the output.

3.2.2.2. Effect of Interference when Three Footings are Closely Spaced

The effect of interference when three-strip footings of widths 50 mm and spaced at different spacings (S/B=1, 2, 3) on unreinforced are also being studied numerically (Figure 3.12). Three footings are considered so that the footing at the middle is under the interference effect from both the footings on either side. The bearing capacity behaviour of the central footing and outer footing are the focus of the study.

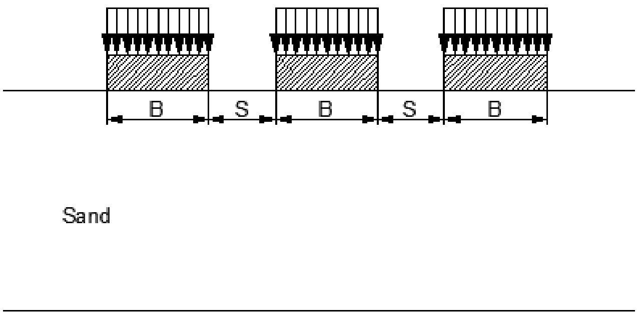


Figure 3.12. Schematic representation of the numerical model with three footings on unreinforced soil

3.3. STUDY ON BEHAVIOUR OF TWO ADJACENT STRIP FOOTINGS ON UNREINFORCED/REINFORCED GRANULAR BED OVERLYING CLAY WITH A VOID

The effects of interference of adjacent footings resting on a granular bed of limited thickness overlying soft clay of great depth with or without voids are numerically studied. Details of all cases of numerical study are summarised in Table 3.1.

In the layered soil, two rigid strip footings each of width, B is considered to be resting on the surface of medium dense sand of finite thickness underlain by a soft clay layer extending to a great extent. This top layer thickness, H represents the depth of the granular bed or granular fill. Surface strip footings of widths 1m and 2m are considered. The distance between the footings is represented in a normalised manner, as the spacing ratio, S/B. The values of S/B considered are 1.0, 1.5, 2.0, 2.5 and 3.0. Two different types of soils are considered, such as medium dense sand and soft clay, forming the top

GB and weak soil layer, respectively. Properties of soils considered are shown in Table 3.6. The diameter of the void is taken as equal to 0.5 times the width of footing for all the cases. The circular void is modelled as a tunnel without lining. In all the cases, voids are considered in the weak soil.

Table 3.6. Properties of soils considered

Properties	Medium dense sand	Soft clay
Material type	Drained	Undrained
Unit weight, γ (kN/m^3)	18.20	16.00
Young's modulus[1], E (kN/m^2)	30000	6000
Poisson's ratio[1], ν	0.28	0.35
Shear strength parameters Cohesion (c) (kN/m^2) Angle of internal friction[2], ϕ (degrees)	0 30^0	20^* 0

[1]After Bowles (2012); [2]Referenced from IS 6403-1981; *undrained shear strength, S_u (kN/m^2)

Finite element analyses of surface strip footings above layered soil with or without voids are carried out using a commercially available program PLAXIS 2D version 2018. The footing is simulated by using 5 node plate elements with properties, modulus of elasticity, E of concrete taken as 25 x10^6 kN/m^2 and Poisson's ratio, ν is considered as 0.15. For vertical and horizontal boundaries of the numerical model are selected suitably after several trials, so as not to affect the results. The boundary should be more than 5-6 times void diameter to provides sufficient lateral space not to restrict the formation of general failure mechanism beneath the footing (Lavasan et al. 2016). Generating finer mesh led to a satisfying result in the numerical analyses when compared with the experimental result in the verification study (Badie and Wang 1984).

3.3.1. Steps Used to Model the Problem Using PLAXIS 2D

The soils are assumed to be elastic perfectly plastic material obeying Mohr-Coulomb model failure criterion in conjunction with a non-associated flow rule ($\phi \neq \Psi$). The difference between ϕ and Ψ represents a non-association plastic flow rule, which means that the plastic potential surface is not identical to the yield surface. The dilation angle has a significant influence on the numerical estimation of bearing capacity. The dilatancy angle, Ψ for medium dense sand is considered as 2/3 of friction angle, ϕ (Ghazavi and Lavasan 2008, Gupta and Sitaram 2020). Plane strain condition and fifteen noded triangular solid elements are used to represent the soil domain. In the case of adjacent strip footings on layered soil mainly bearing capacity aspect is focused. So, an ideal elastic perfectly plastic soil model is sufficient. The loading path has no significant influence on the failure state in bearing capacity analysis (Ghazavi and Lavasan 2008; Lavasan et al. 2016). But for the deformation analysis, more sophisticated constitutive models are required. The rigid surface strip footings are considered. The footing width B is taken to be 1 and 2m, and the soil domain is 10B away from the footing's edge on either side, and 10B in depth to reduce the possible boundary effects. The bottom horizontal boundary is fixed in both the vertical and horizontal directions, and the side boundary is restricted only along the horizontal direction. A fine mesh is adopted in the study.

Finite element calculation is done by staged construction procedure. In the initial stage, initial stresses in the soil are generated by the K_0 procedure. In the first phase, the weak soil layer and the granular bed above the weak soil is activated. Footings are activated in the next stage and soil inside the void space is deactivated to simulate the void space, and in the later stage, line loading is simulated. An automatic load stepping procedure terminates the calculation when the specified state or load level (ultimate state or ultimate level) is reached or when soil failure is detected. If at the end of the calculation, the defined state or load level has been reached, the calculation is considered to be successful. If the defined state or load level has not been reached, the calculation is considered to have failed and collapse load is noted.

3.3.2. Study on Behaviour of Two Adjacent Strip Footings on Unreinforced Granular Bed Overlying Clay with A Void

This numerical study attempts to study interference of adjacent footings which are loaded (i) equally and simultaneously (ii) unequally and sequentially, which are very common practical cases. The top layer thickness of medium dense sand (H) is varied as 1.0B and 1.5B. Figures 3.13 a-c represent single strip footing on layered soil. Figures

3.14 a-b represent two adjacent strip footings on layered soil without any void. Figures 3.15a-b represent two adjacent strip footings with voids beneath in soft soil, simultaneously loaded. Figures 3.16 a-c represent two adjacent strip footings with voids beneath in soft soil, sequentially loaded. In the first loading condition (simultaneous loading), both the strip footings are loaded equally up to failure. In the second loading condition (sequential loading), one of the strip footings representing an already existing foundation is loaded with half of the estimated failure load of single strip footing, and adjacent new strip footing loaded up to failure. To study the effect of void under footings in the layered soil system, firstly a single void is considered beneath a single strip footing (Figures 3.13 b-c). X and Y are as shown in figures 3.13 b-c. In the case of two footings, a single void is considered at different positions as seen in figures 3.15 a-b; 3.16 a-c.

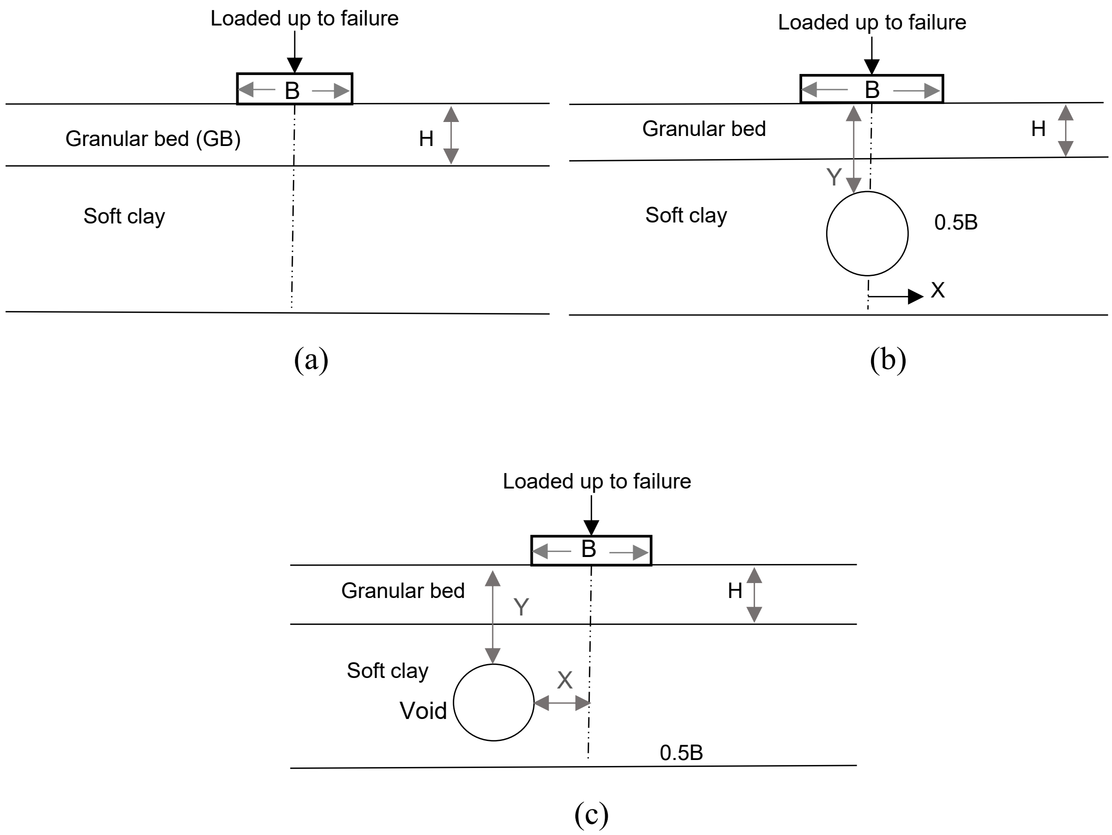
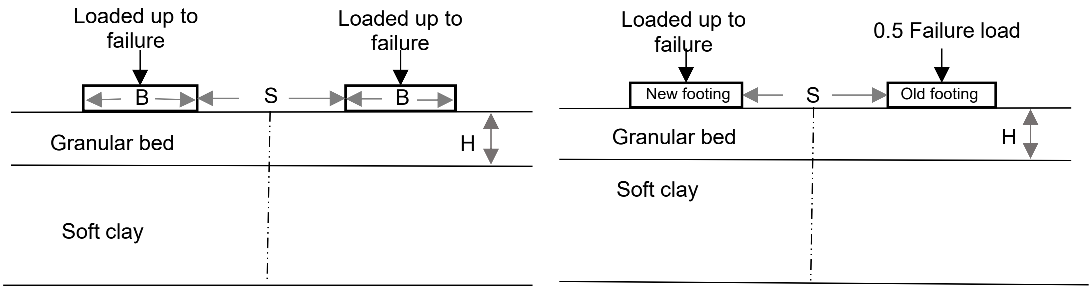
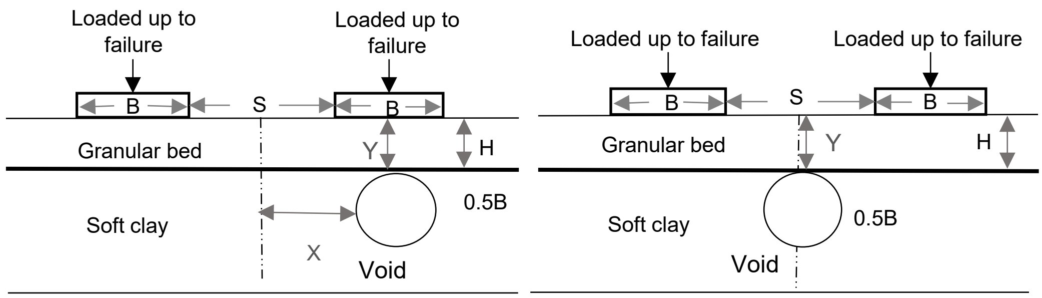


Figure 3.13. Single strip footing on GB overlying weak soil (a) without void loaded up to failure (b) with void loaded up to failure (c) definition sketch for parameters X and Y (not drawn to scale)



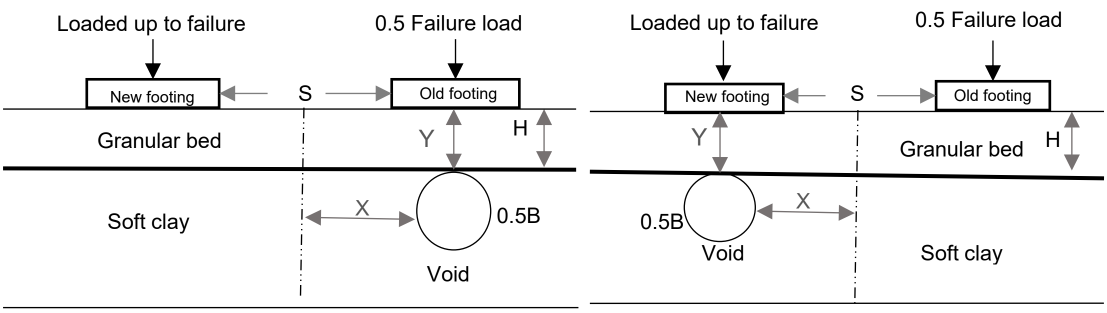
(a) (b)

Figure 3.14. Two adjacent strip footings on GB overlying weak soil layer without any void (a) simultaneous loading (b) sequential loading (not drawn to scale)

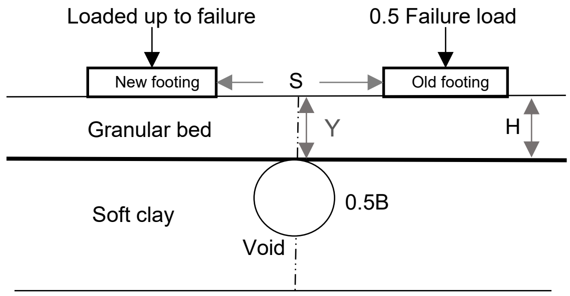


(a) (b)

Figure 3.15. Two adjacent strip footings on GB overlying weak soil with a void, simultaneously loaded (a) void below one of the footings (b) void at midpoint between the two footings (not drawn to scale)



(a) (b)



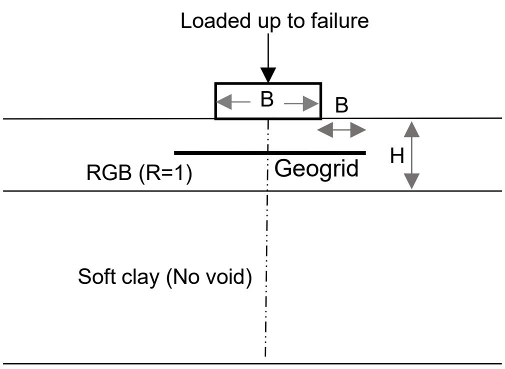
(c)

Figure 3.16. Two adjacent strip footings on GB overlying weak soil with a void, sequentially loaded (a) void below old footing (b) void below new footing (c) void at midpoint between the two footings (not drawn to scale)

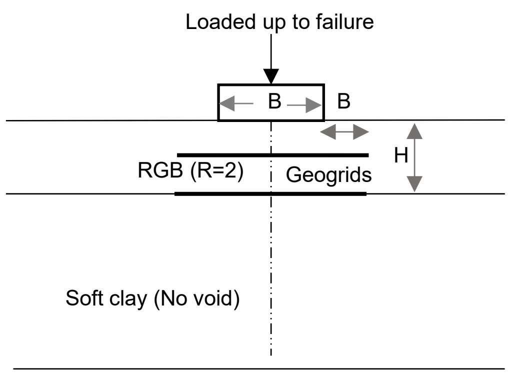
3.3.3. Study on Behaviour of Two Adjacent Strip Footings on Reinforced Granular Bed Overlying Clay with Voids

The effects of interference of adjacent footings resting on an unreinforced (GB) and reinforced granular bed (RGB) of limited thickness overlying soft clay of great depth with or without voids are studied. Both the strip footings are loaded simultaneously up to failure. Two rigid strip footings each of width B are considered to be resting on medium dense sand of finite thickness adjacent to each other, overlying soft clay extending to a large extent. The top layer thickness of medium dense sand (H) is varied as 0.75B, 1.0B, 1.5B and 2.0B. Surface strip footings of widths 1m and 2m are considered. Geogrid is considered as reinforcement in this study. The reinforcement layers were modelled according to the in-built 5 node geogrid material option integrated into the program with its axial rigidity (EA) taken as 500 kN/m. A shear directed frictional interaction is considered between the geogrid and soil (Rinter=0.8). The reinforcements are placed at B/2 depth from the top surface of the soil bed in both the cases of single-layer and two layers of reinforcement. In the case that there are two layers, the distance between the reinforcements is B/2. For all cases, the diameter of the void is taken as 0.5B and considered in the weak soil. The circular void is modelled as a tunnel without lining.

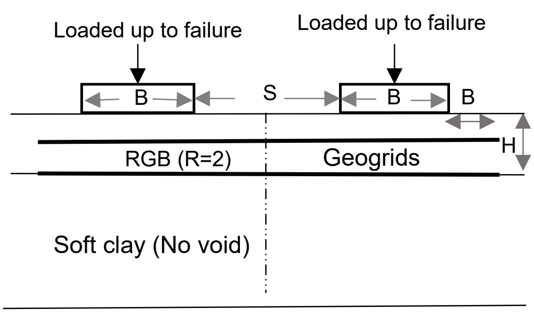
Firstly, analyses are conducted for single independent strip footing (Figures 3.17 a-b, 3.18 a-b). Further analyses are conducted with two strip footings resting on the surface (Figures 3.17 c-f, 3.18 c-g). The length of the reinforcement beneath two adjacent strip footings is provided in two types, such as continuous and discontinuous reinforcement. In the continuous case, the reinforcement extends a ‘B’ distance from the outer edges of the strip footing horizontally (Figures 3.17 c-d; 3.18 d-e), and in discontinuous case, the reinforcement extends a ‘0.5B’ distance from either edge of the individual strip footing horizontally (Figures 3.17 e-f; 3.18 f-g). To study the effect of void under footings in the layered soil system, RGB overlying weak soil, firstly a single void is considered beneath a single strip footing (Figures 3.18a-b). Properties of voids considered are shown in Table 3.7.



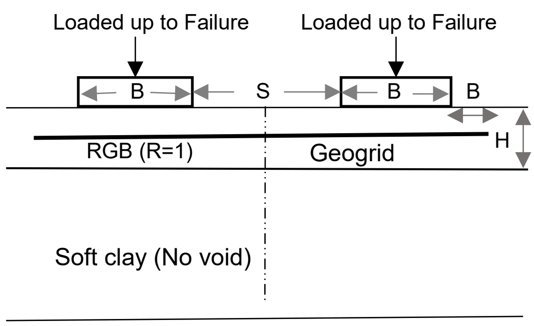
(a) Single strip footing (R=1)



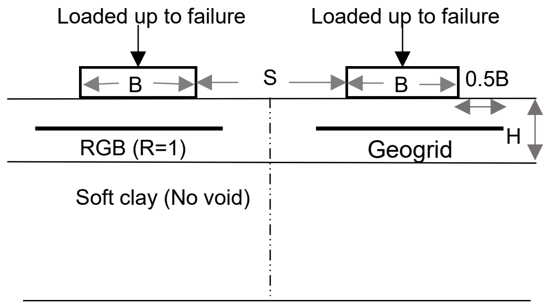
(b) Single strip footing (R=2)



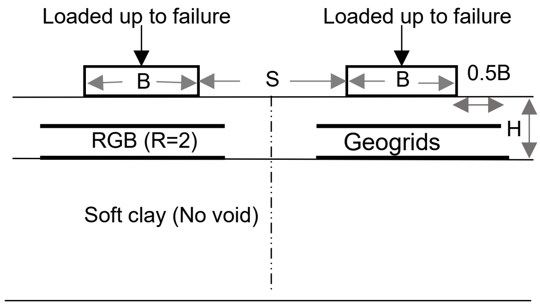
(c) Continuous reinforcement (R=1)



(d) Continuous reinforcement (R=2)

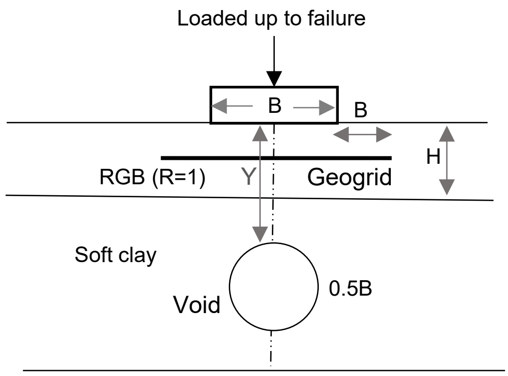


(e) Discontinuous reinforcement (R=1)

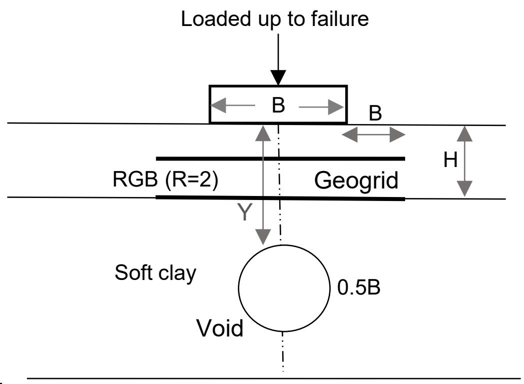


(f) Discontinuous reinforcement (R=2)

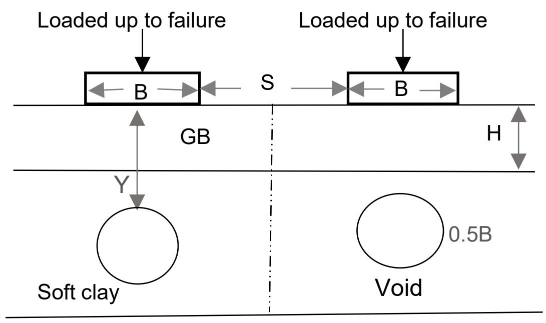
Figure 3.17. Footing/s on the top of reinforced granular bed (RGB) overlying weak soil layer without any voids (R-Number of reinforcement layers) (a-f) (not drawn to scale)



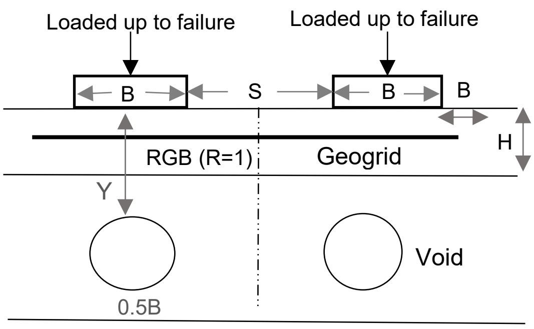
(a) Single strip footing (R=1)



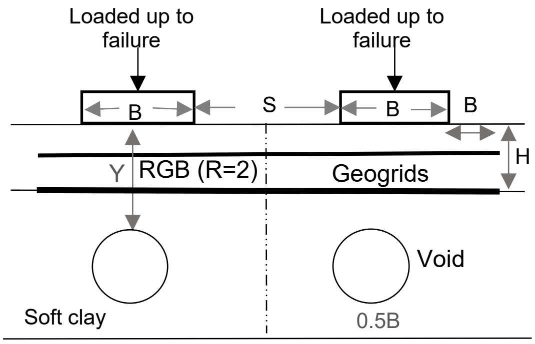
(b) Single strip footing (R=2)



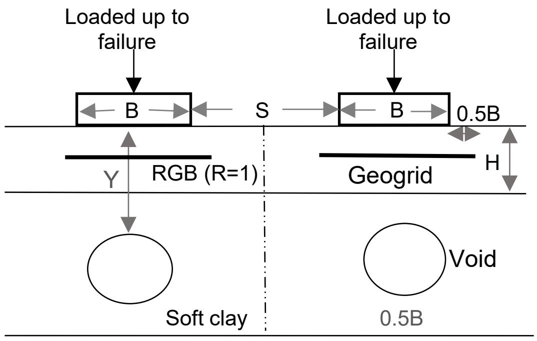
(c) Unreinforced



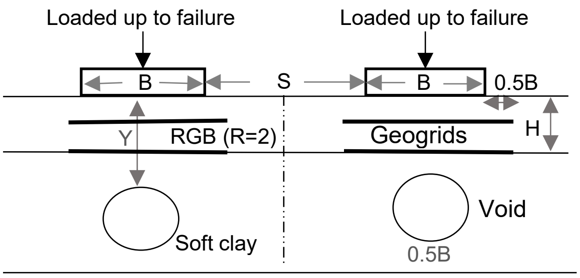
(d) Continuous reinforcement (R=1)



(e) Continuous reinforcement (R=2)



(f) Discontinuous reinforcement (R=1)



(g) Discontinuous reinforcement (R=2)

Figure 3.18. Footing/s on the top of granular bed (GB or RGB) overlying weak soil layer with void/s (a-g) (not drawn to scale)

Table 3.7. Properties of voids considered

Case	Number of voids	Position of voids
Isolated footing on unreinforced granular bed over clay	1	X/B=0,1,2,3 Y/B=1,1.5,2,3,4,5
Two footings on unreinforced granular bed over clay (Simultaneous loading)	1	Below the centre of one of footing, midpoint between the footings
Two footings on unreinforced granular bed over clay (Sequential loading)	1	Below the centre of old footing, below the centre of new footing, midpoint between the footings
Isolated footing on reinforced granular bed over clay R=1,2	1	Below centre of footing X/B=0 Y/B=1.5,2,3,4,5
Two footings on unreinforced granular bed over clay (Simultaneous loading)	2	Below the centre of each footing (Y/B=1.5, X/B=0)
Two footings on reinforced granular bed over clay (Simultaneous loading) R=1,2 (Continuous and discontinuous reinforcement)	2	Below the centre of each footing (Y/B=1.5, X/B=0)

CHAPTER 4

RESULTS AND DISCUSSION

4.1. GENERAL

This chapter deals with analysis of the experimental and numerical results. The results of the study are presented and discussed with reference to the main aim of the study. A comparison between results obtained from experimental studies and those obtained from finite element analyses are given in the first section. The experimental analyses are carried out in the unreinforced and reinforced granular soil on adjacent strip footings. Two different footings of widths, such as 50mm and 100mm, are used in the model tests. The numerical analyses are carried out by PLAXIS version 2018.

The interference effect of granular bed overlying soft clay with or without voids are explained in the later section. Parameters such as footing width, granular bed thickness, spacing between the footings, reinforcement characteristics, number of voids and void position are considered. All analyses in this section are done numerically.

4.2. EXPERIMENTAL AND NUMERICAL INTERFERENCE STUDIES OF ADJACENT STRIP FOOTINGS ON UNREINFORCED AND REINFORCED MEDIUM DENSE SAND

In the experimental studies, laboratory-scale plate load tests are conducted. Single independent footing and two adjacent strip footings are considered on unreinforced and reinforced granular soil. Reinforcements used are in the form of hexagonal wire meshes. The interference factor is used to quantify the interference in terms of bearing capacity and settlement. The experimental results are complemented with numerical analyses in the case of simultaneous loading case.

4.2.1. Both the Footings Loaded Simultaneously till Failure

4.2.1.1. Interference of Two Strip Footings on Unreinforced Soil

i) Variation of interference factor of bearing capacity (IF_1) with spacing between the footings

Bearing pressure-normalised settlement plots of single strip footings of width 50 mm and 100 mm and two closely spaced strip footings placed on unreinforced cohesionless soil are shown in figures 4.1, and 4.2. Spacing between the footings 'S' is varied from 1B to 4B in both experimental and numerical studies for 50 mm wide footing. Spacing between the footings 'S' is varied from 1B to 3B in both experimental and numerical studies for 100 mm wide footing. The bearing pressure-settlement curves are plotted with settlement (s) normalised with twice the width of the footing (2B), where 2B is considered to be the depth of the influence zone beneath the footing. From figures 4.1 and 4.2, it can be inferred that there is reasonably good agreement between numerical results and experimental results. To study the effect of interference of two closely spaced strip footings on the bearing capacity of soil; interference factor of bearing capacity (IF_1) is determined in each case from the bearing pressure-settlement plots. The interference factor of bearing capacity (IF_1) is defined as follows in Equation 4.1.

$$IF_1 = \frac{\text{Ultimate load carrying capacity of the footing in question in presence of an adjacent footing}}{\text{Ultimate load carrying capacity of single independent strip footing}} \quad (4.1)$$

The ultimate bearing capacities are obtained from the bearing pressure-settlement curves. It is observed that in the case of two strip footings on unreinforced soil, the effect of interference (represented by IF_1) at first increases as the spacing between the footing is increased from S/B=1 to 2. Thereafter, the IF_1 of bearing capacity value decreases beyond the spacing of S/B=2 (Figure 4.3). The behaviour of interference effect can be due to the so-called "blocking effect". Because of this influence, the soil between the two footings forms an inverted arch and the combined system moves down upon loading as a single unit. Since the area of this single unit is larger than the combined area of the two footings, it has a higher bearing capacity. Figure 4.4 shows a comparison of the interference factors obtained from the present study with those reported in the literature. The interference factors obtained in the present study are in reasonably good agreement.

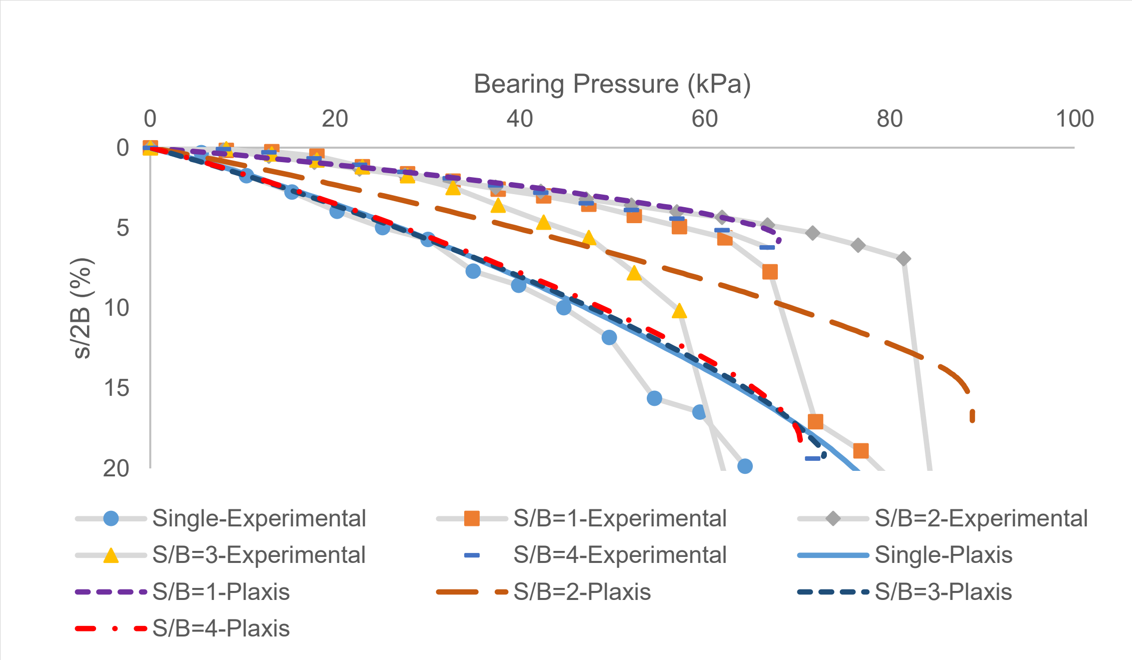


Figure 4.1. Bearing pressure- normalised settlement curves for single and two adjacent strip footings on unreinforced soil from both experimental and numerical studies (with 50 mm wide strip footings)

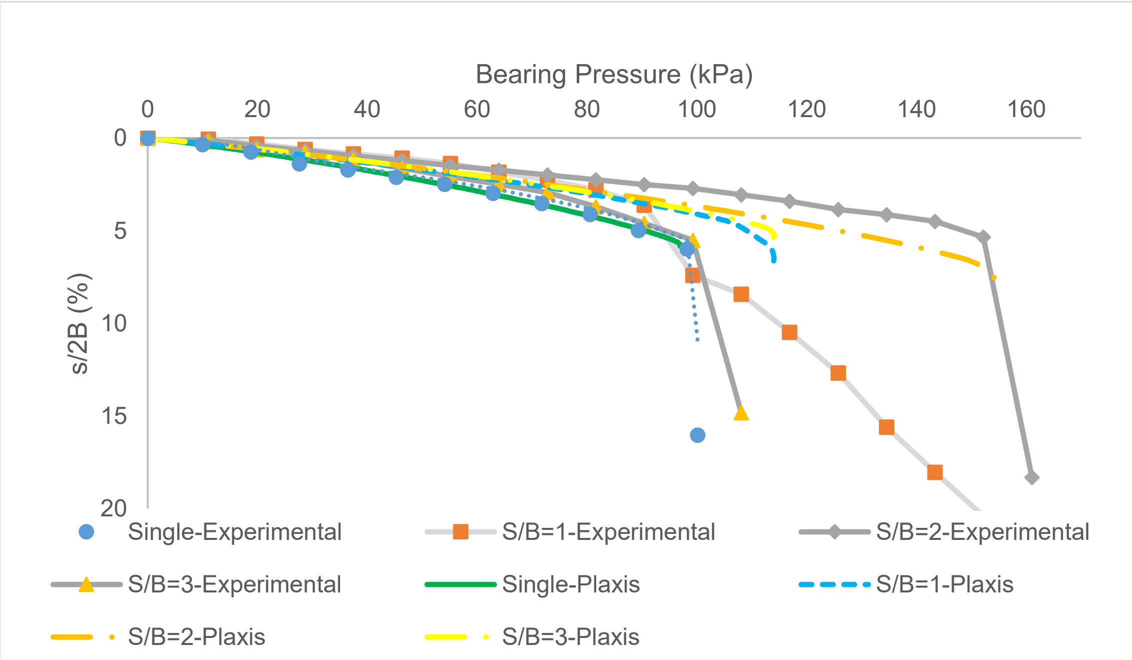


Figure 4.2. Bearing pressure-normalised settlement curves for single and two adjacent strip footings on unreinforced soil from both experimental and numerical studies (with 100 mm wide strip footings)

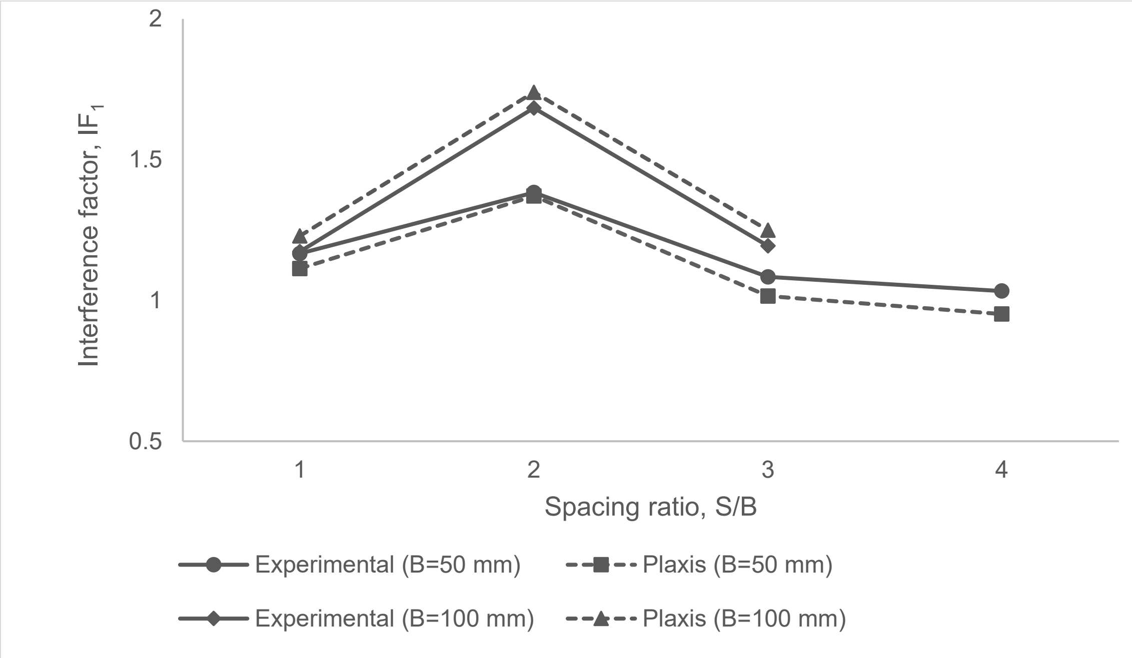


Figure 4.3. Variation of interference factor (IF_1) of bearing capacity with spacing ratio, S/B, for footing widths of 50 mm and 100 mm from experimental and numerical studies (Unreinforced foundation soil)

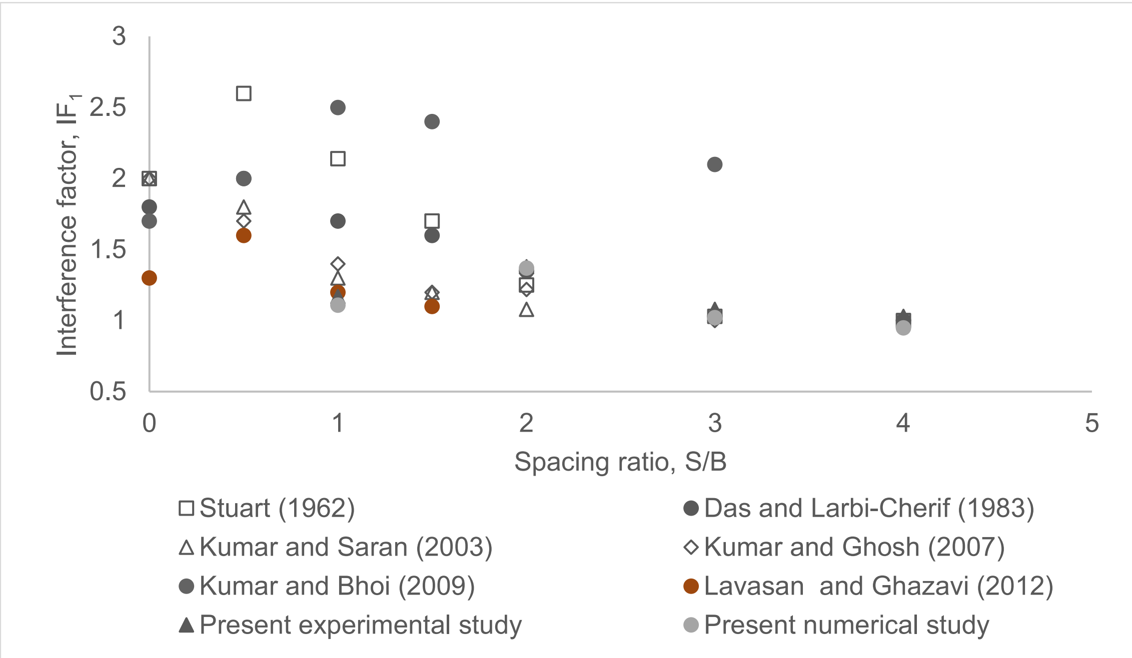


Figure 4.4. Comparison of interference factor of bearing capacity (IF_1) with spacing ratio, S/B, for footing widths of 50 mm from the present experimental and numerical studies (Unreinforced foundation soil) with previous studies

ii)Increase in confining pressure due to interference

A series of numerical models for all four spacings between footings are conducted to study the variation in confinement pressure due to the effect of interference between two footings. Horizontal pressure ($\log_{10}\sigma'_{xx}$) at the midway between the footings at 0.5B distance below the surface was traced against the settlement of footing at 0.5B distance below the surface. The results are presented, as shown in figure 4.5. It is seen therein that maximum confinement pressure is generated at S/B=1 when settlement is about 5%, and at S/B=2 when the settlement is more than about 15%. This is in good agreement with the interference factor peaking at S/B value of around 2.0, as shown in figure 4.3. Gupta and Sitaram (2020) also studied the increase in confining pressures due to interference.

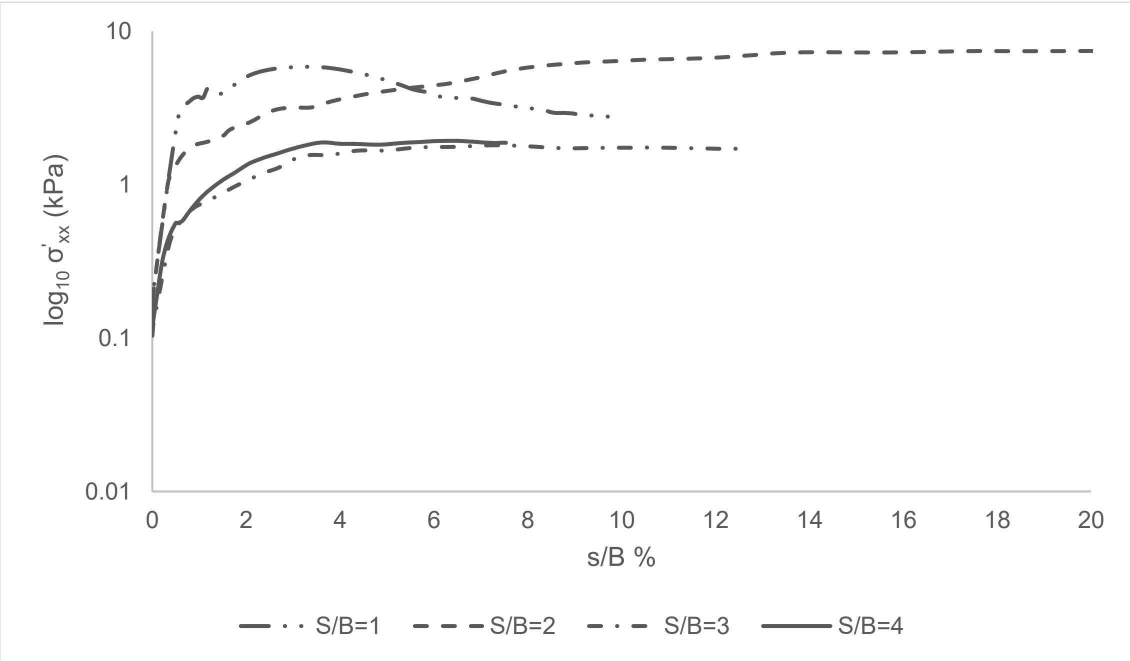


Figure 4.5. Variation of confining pressure σ'_{xx} (midway between two footings at depth 0.5B below the surface) v/s normalised settlement of footing for footing width 50mm (from numerical study)

iii)Variation of the interference factor of settlement (ξ_δ) with spacing between the footings

To study the effect of interference of two closely spaced strip footings on the settlement behaviour of soil; the interference factor of settlement (ξ_δ) is determined in each case from the bearing pressure-settlement plots. The interference factor due to settlement (ξ_δ) can be defined as follows.

$$\xi_\delta = \frac{\text{Settlement of a footing in the presence of an adjacent footing at its ultimate bearing capacity}}{\text{Settlement of single independent strip footing at its ultimate bearing capacity}} \quad (4.2)$$

The variation of the interference factor (ξ_δ) with respect to spacing ratio S/B are shown in figure 4.6. The interference factor of settlement (ξ_δ) is also seen to attains its peak value at S/B=2. Two 50mm wide strip footings placed adjacent to each other are seen to settle less than a single strip footing of 50 mm width. Two 100 mm wide footings placed adjacent to each other are seen to settle more than two 50 mm wide strip footings placed adjacent to each other. At S/B=2, two 100 mm wide strip footings are seen to settle considerably more than a single strip footing of 100 mm width (Figure 4.6).

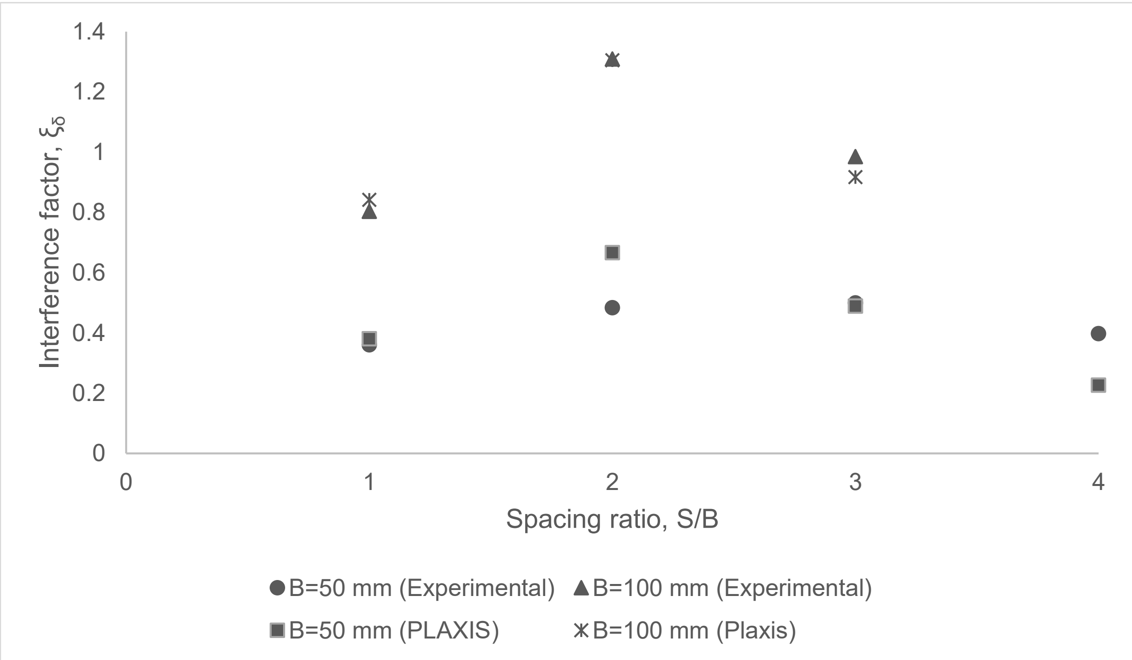


Figure 4.6. Variation of interference factor of settlement (ξ_δ) with spacing ratio (S/B), for footing widths of 50 mm and 100 mm from experimental and numerical studies (Unreinforced foundation soil)

4.2.1.2. Interference of two strip footings on reinforced soil

i) Single and independent strip footings on reinforced soil

Single strip footings are placed on reinforced soil. Bearing pressure-normalised settlement plots of single strip footings of width 50 mm and 100 mm and two closely spaced strip footings placed on reinforced cohesionless soil are shown in figures 4.7-4.10. The bearing capacity increases with the inclusion of reinforcement in the soil bed and also that the bearing capacity increases with the increase in the number of reinforcement layers. The effect of increasing the number of reinforcement layers on ultimate bearing capacity can be studied by analysing the Bearing Capacity Ratio (BCR) values, which help to quantify the same. Bearing Capacity Ratio (BCR) is defined as in Equation 4.3.

$$\text{BCR}=\frac{\text{Ultimate bearing capacity of footing on reinforced soil}}{\text{Ultimate bearing capacity of footing on unreinforced soil}} \tag{4.3}$$

Significant improvement in bearing capacity for single footing with three layers of reinforcement as compared to a single layer of reinforcement can be seen in figure 4.11. The strength and stiffness of the foundation soil are increased by virtue of providing reinforcements or inclusions in soils. Also, the confinement of the soil beneath footing is somewhat increased due to the reinforcements.

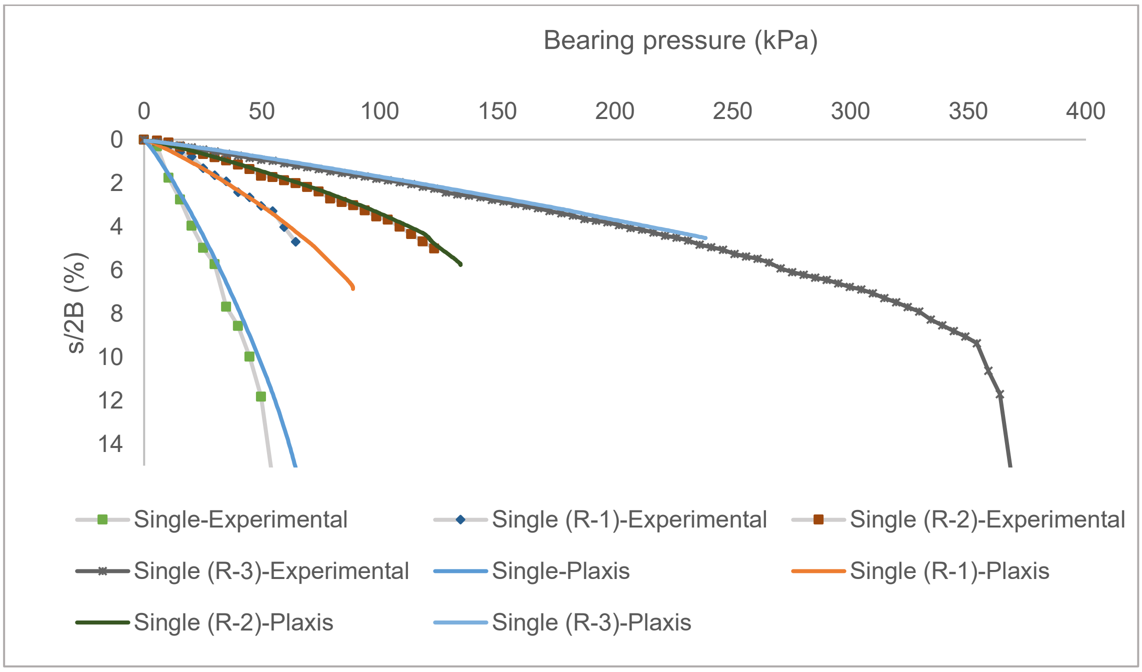


Figure 4.7. Bearing pressure- normalised settlement curves for single strip footings on reinforced soil from both experimental and numerical studies (with 50 mm wide strip footings)

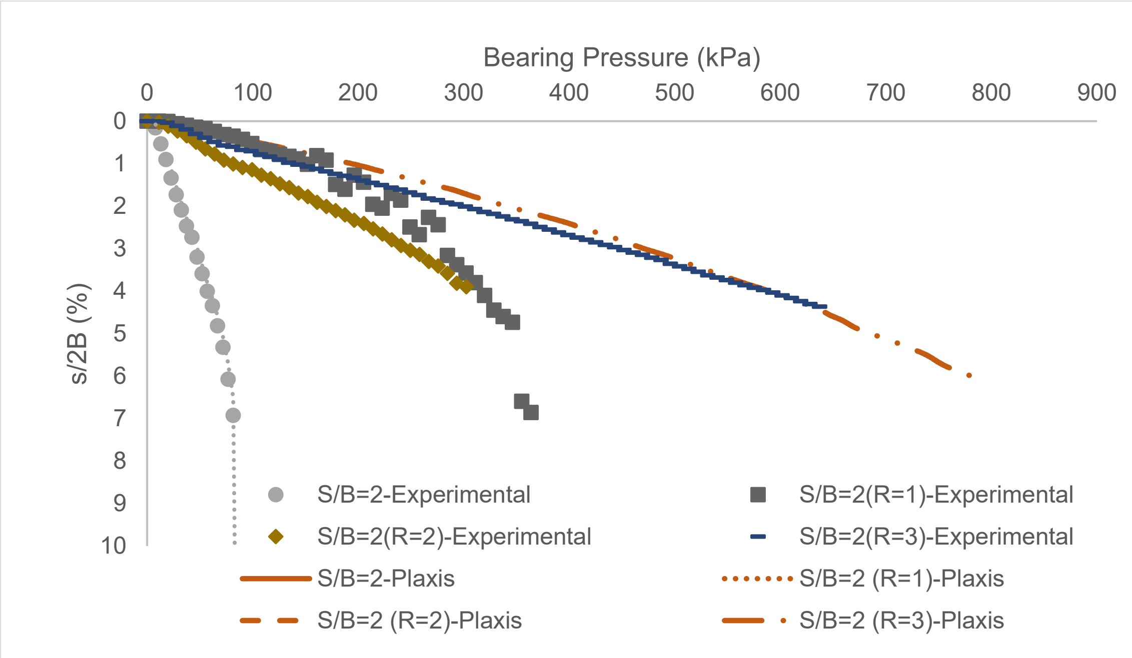


Figure 4.8. Bearing pressure- normalised settlement curves for two adjacent strip footings on reinforced soil from both experimental and numerical studies (with 50 mm wide strip footings)

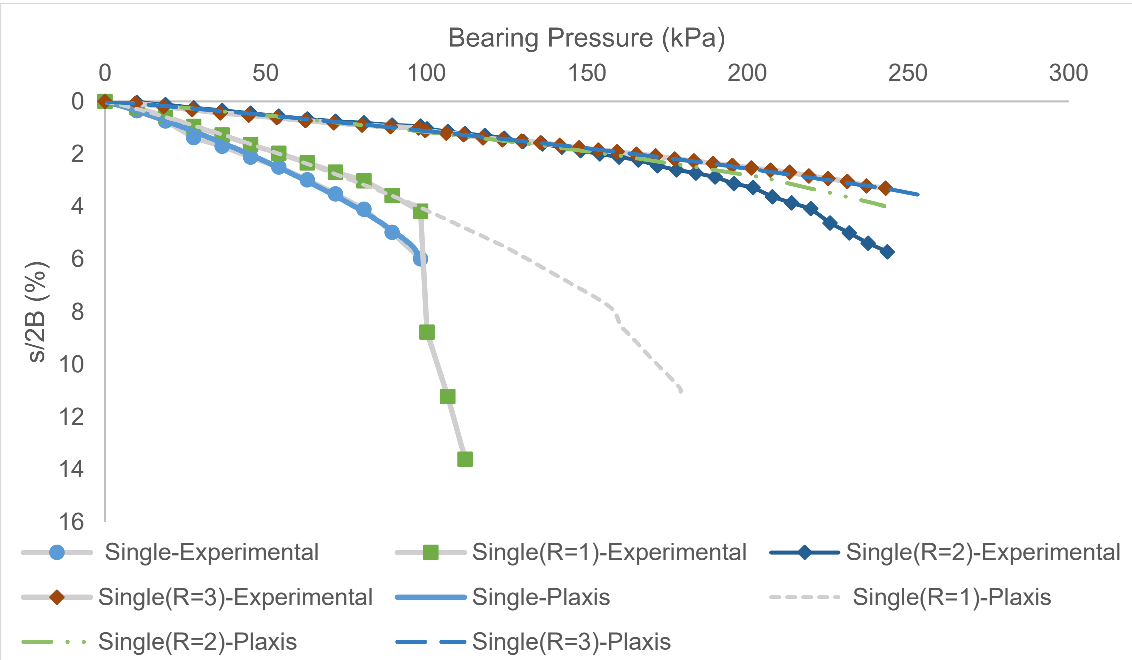


Figure 4.9. Bearing pressure-normalised settlement curves for single strip footings on reinforced soil from both experimental and numerical studies (with 100 mm wide strip footings)

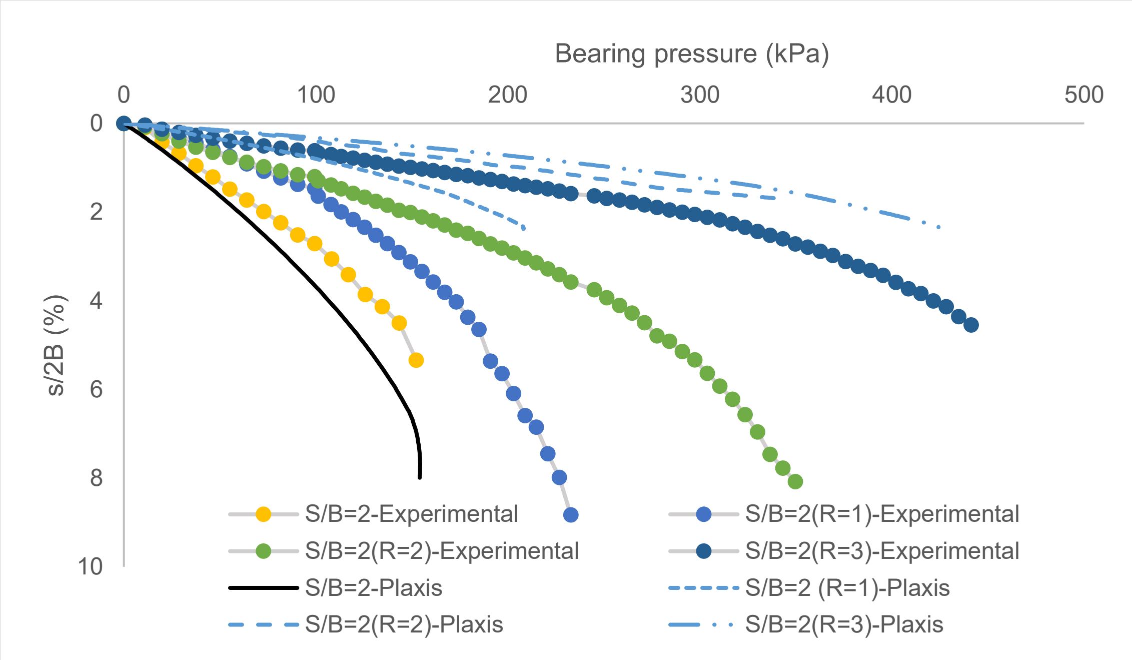


Figure 4.10. Bearing pressure-normalised settlement curves for two adjacent strip footings on reinforced soil from both experimental and numerical studies (with 100 mm wide strip footings)

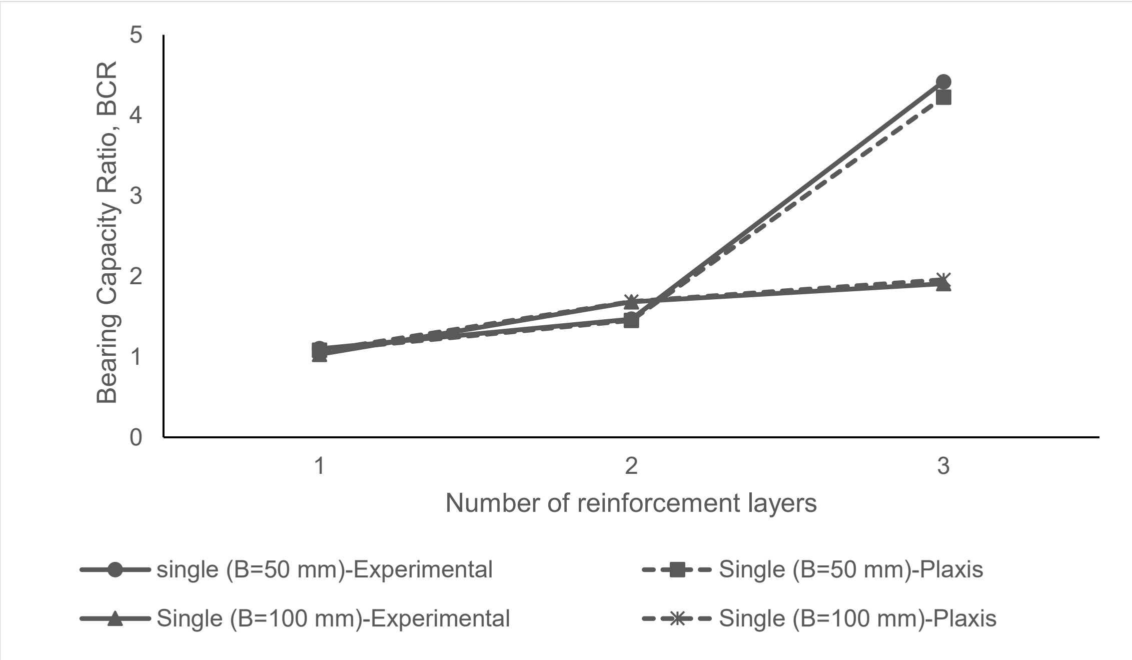


Figure 4.11. Variation of Bearing Capacity Ratio (BCR) with the number of reinforcement layers for footing widths of 50 mm and 100 mm from experimental and numerical studies

ii) Two adjacent strip footings on reinforced soil

Tests with reinforced soil conditions are conducted with spacing between two strip footings kept at 2B. The effect of reinforcement on the bearing capacity of two adjacent strip footings placed on reinforced soil is studied by analysing the Modified Bearing Capacity Ratio (MBCR) values. Modified Bearing Capacity Ratio (MBCR) is defined, as shown in Equation 4.4.

$$\mathrm{MBCR} = \frac{\text{Ultimate bearing capacity of the footing in question in presence of an adjacent footing on reinforced soil}}{\text{Ultimate bearing capacity of the same footing in presence of an adjacent footing on unreinforced soil}} \quad (4.4)$$

Variations in Modified Bearing Capacity Ratio (MBCR) with the number of reinforcement layers for footing widths 50 mm and 100 mm from experimental and numerical studies are plotted in figure 4.12. Modified bearing capacity ratio increases with the number of reinforcement layers. MBCR highlights the increase in bearing capacity due to reinforcing the foundation soil, in the presence of adjacent footing, and it excludes the interference effects.

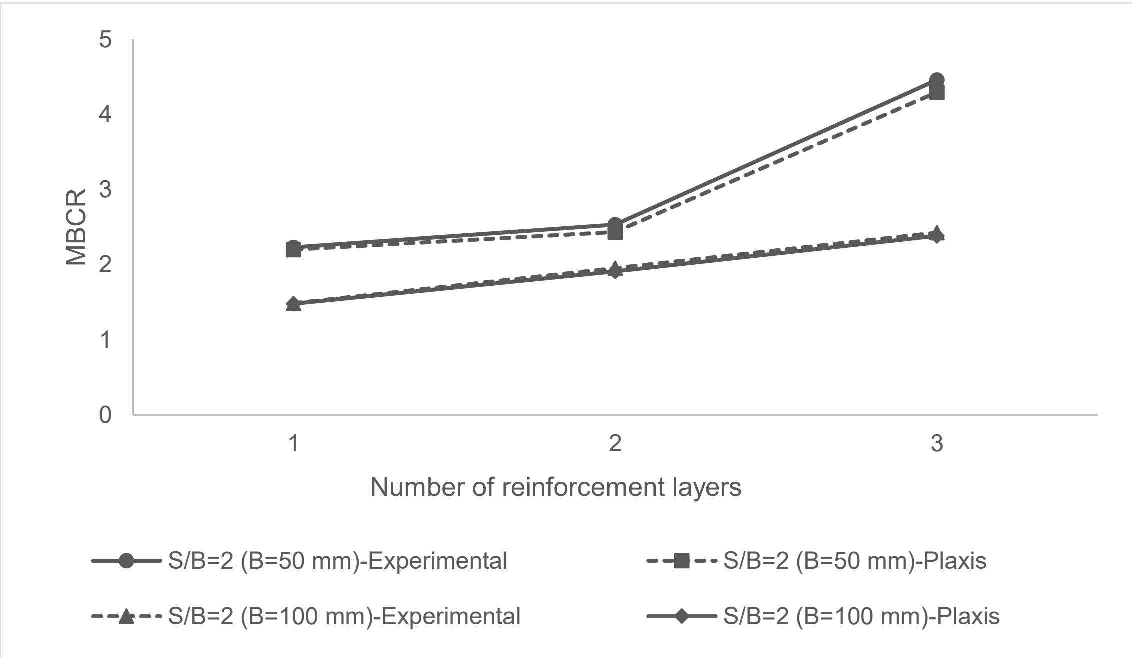


Figure 4.12. Variation in Modified Bearing Capacity Ratio (MBCR) with the number of reinforcement layers for footing widths of 50 mm and 100 mm from experimental and numerical studies

The effect of interference of two adjacent strip footings, placed on reinforced soil is being studied by analysing the interference factor due to reinforcement (IFr). The interference factor due to reinforcement (IFr) is defined as shown in Equation 4.5.

$$\text{IFr} = \frac{\text{Ultimate bearing capacity of the footing in question in presence of an adjacent footing on reinforced soil}}{\text{Ultimate bearing capacity of a single independent strip footing on reinforced soil}} \quad (4.5)$$

The interference factor due to reinforcement (IFr) is plotted with respect to the number of reinforcement layers (Figure 4.13). Interference factors of bearing capacity (IF_1) of two footings on unreinforced soil (Figure 4.3) are in the range of 1 to 1.75 for S/B values 1 to 4. In figure 4.3, IF_1 increases for S/B values 1 to 2 and then decreases somewhat. However, with reinforcement in foundation soil and for S/B=2 values of IFr are between 2 and 3 up to two layers of reinforcements, and IFr is between 2 and 5 for three layers of reinforcement. This indicates that the presence of reinforcement beneath two adjacent footings enhances the interference (of bearing capacity) effect.

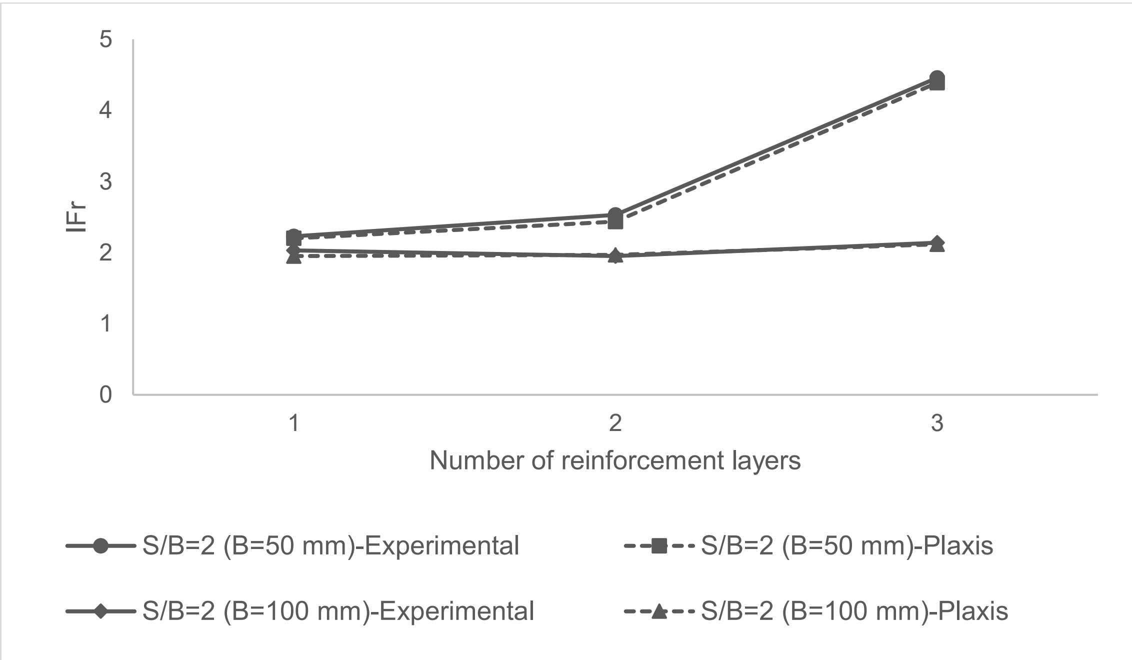
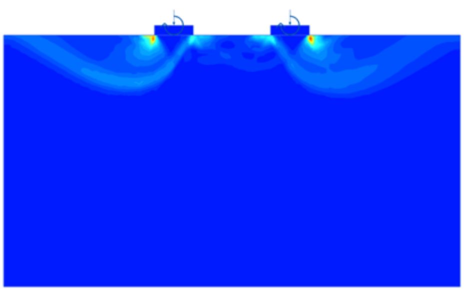


Figure 4.13. Variation in interference factor due to reinforcement (IFr) with the number of reinforcement layers for footing widths of 50 mm and 100 mm from experimental and numerical studies

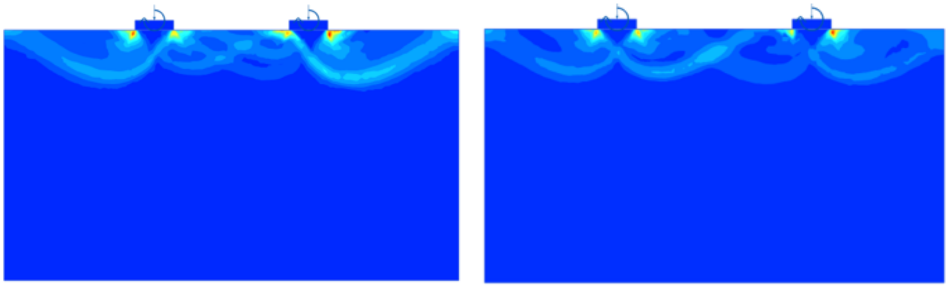
4.2.1.3. Study of the Failure Surfaces

To study the failure mechanism of adjacent footings at failure load, incremental shear strain contours are considered. The incremental shear strain contours in the case of 50 mm single strip footing and interfering footings (S/B=1 to 4) on unreinforced soil, is shown in figure 4.14. The failure zones under footings converge to each other towards the inner side between two footings at closer spacings. At the same time, it increases the size of failure zones on the outer sides of each footing significantly increase. Even though the failure mechanism is symmetric, the failure and deformation patterns beneath each footing are asymmetric. The failure zones are transformed into a symmetrical shape by extending the distance between two neighbouring footings. Propagation of slip surfaces in single strip footing is symmetric on either side of the footing (Lavasan and Ghazavi 2014). The failure mechanism in the case of reinforced soils differs from the unreinforced case. In the case of the reinforced foundation soil, the slip surfaces seem to emerge from beneath the reinforcement layers. By an increase in the number of reinforcement layers, influence the depth of foundation soil would increase. Reinforcements prevent the concentration of stresses at zones around or beneath the footing. It leads to a reduction in settlement and results in a somewhat more uniform settlement of soil beneath the footing (Lavasan and Ghazavi 2014). When the footing is provided with a number of layers of reinforcement, the failure surface is also seen to get broader and deeper (Figure 4.15). An idea of the progressive development of shear strain as the loading on the footings (50 mm width) increases can be seen in figure 4.16.

(a) S/B=1

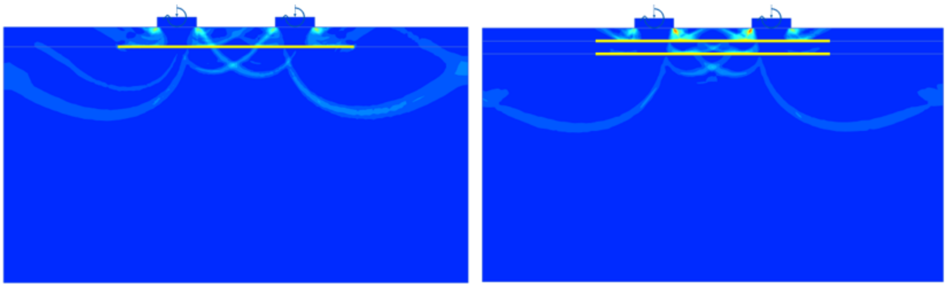


(b) S/B=2



(c) S/B=3 (d) S/B=4

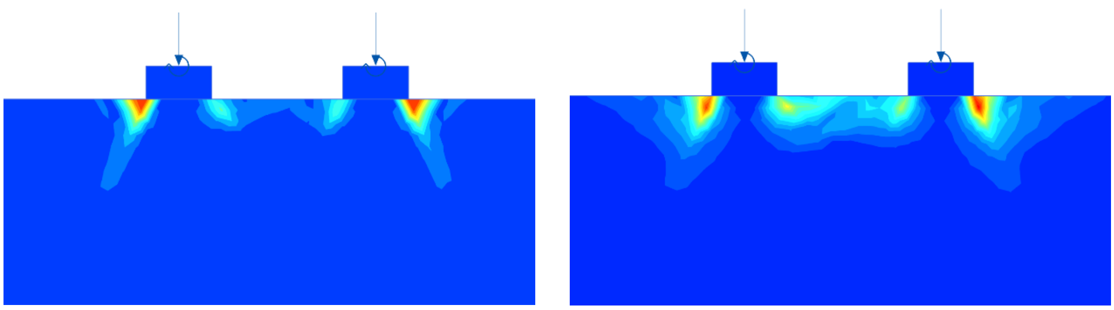
Figure 4.14. Incremental shear strain contour at failure in the case of 50mm footing (a-d) two adjacent strip footing with S/B=1, 2, 3, 4 on unreinforced soil



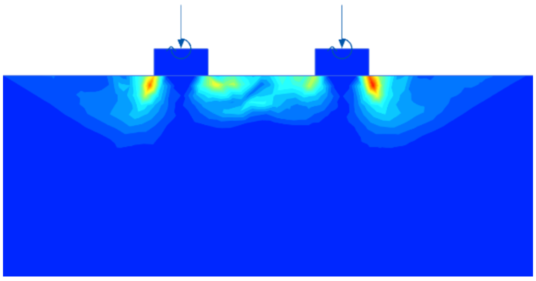
(a) S/B=2 (R=1) (b) S/B=2 (R=2)

(c) S/B=2 (R=3)

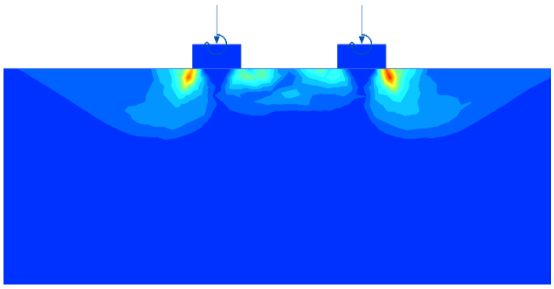
Figure 4.15. Incremental shear strain contour at failure in the case of 50mm footing on reinforced soil for S/B=2 (a) R=1 (b) R=2 (c) R=3 where R stands for the number of layers of reinforcement



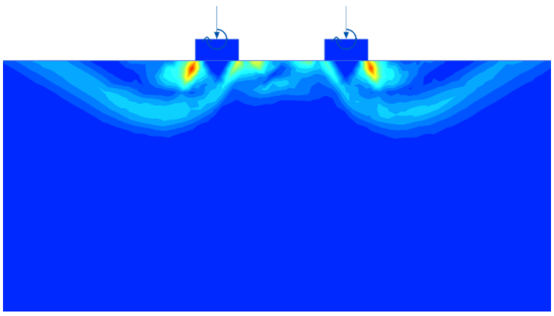
(a) at $0.25q_u$ of single footing (b) at $0.5q_u$ of single footing



(c) at $0.75q_u$ of single footing



(d) at q_u of single footing



(e) at failure load

Figure 4.16. Progressive shear strain contours for S/B=2 of 50 mm footing at loads of (a) $0.25q_u$ of single footing (b) $0.5q_u$ of single footing (c) $0.75q_u$ of single footing (d) q_u of single footing (e) Failure load

4.2.1.4. Interference Effect on the Tilt of Footings

The tilt of footings on unreinforced and reinforced soils are also being studied numerically. Tilt is expressed in terms of percentage. Tilt is plotted against the spacing ratio, S/B for unreinforced soil for different footing widths (Figure 4.17). Tilt is observed to increase with a decrease in spacing between the footings. In the case of footings on reinforced soil, tilt is plotted against the number of reinforcement layers for the two footing widths (Figure 4.18). The tilt of footing is found to be reduced when there is reinforcement beneath the footing. Tilt decreases with an increase in the number of layers of reinforcement. The tilt of footings, when they are loaded simultaneously, on unreinforced and reinforced soils are observed to follow a similar trend as that reported by Lavasan and Ghazavi (2012).

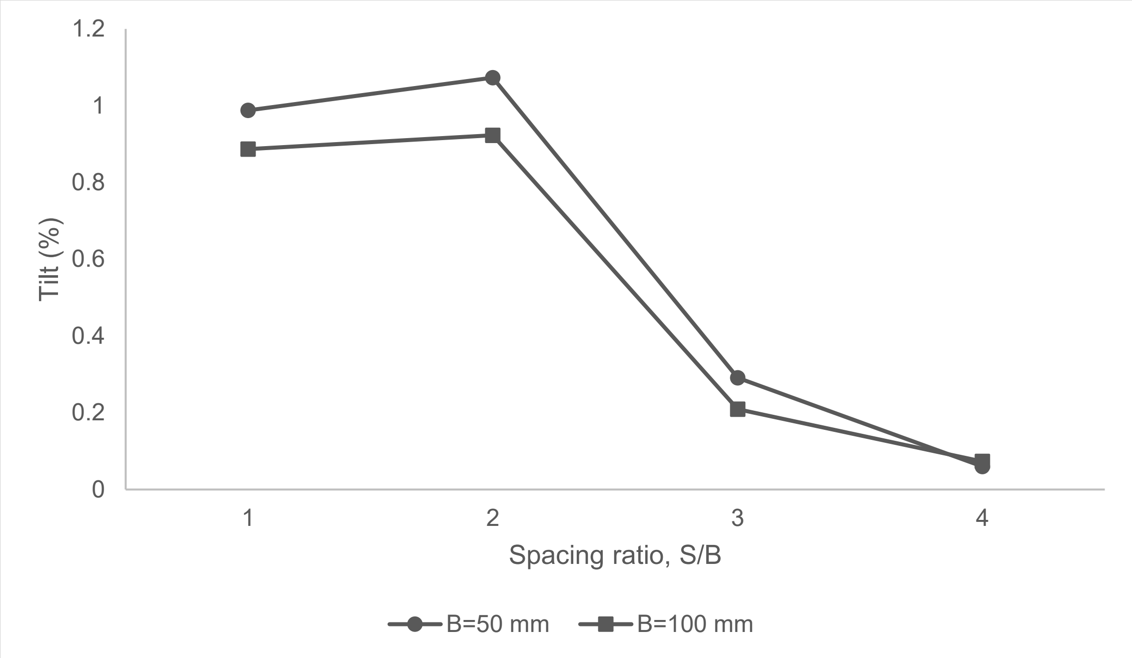


Figure 4.17. Tilt of footing versus spacing ratio, S/B, for unreinforced soil conditions for footing widths 50 and 100 mm from numerical studies

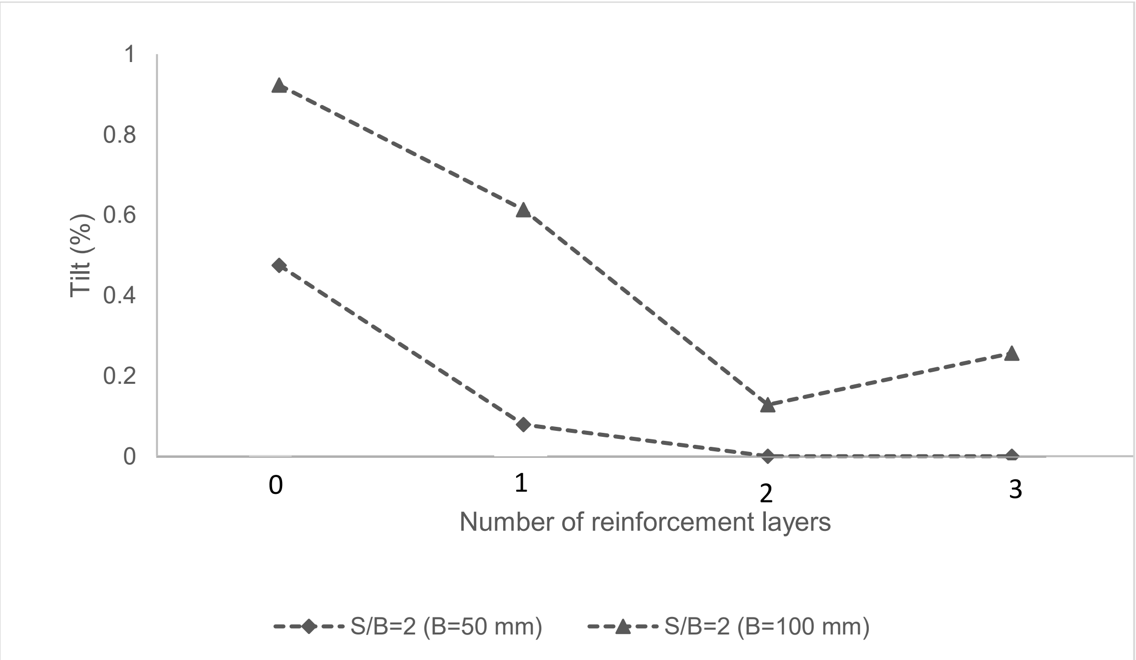
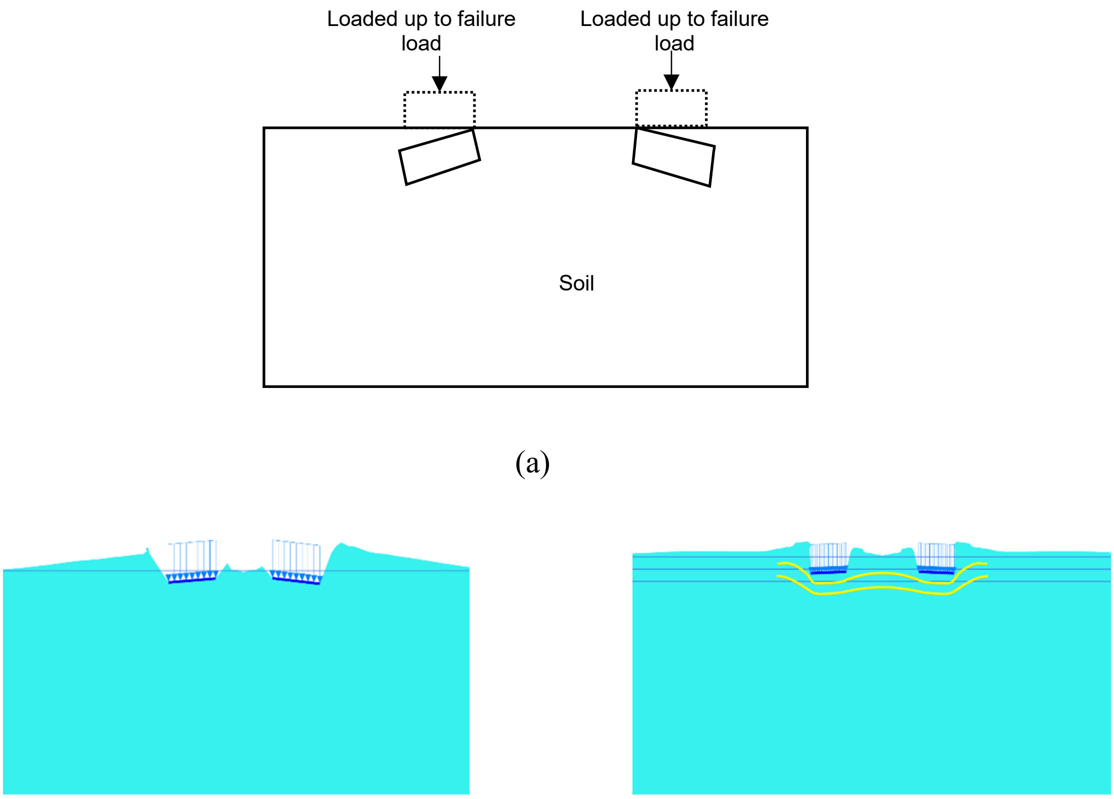


Figure 4.18. Tilt of footing versus number of reinforcement layers for footing widths 50 mm and 100 mm (for S/B=2, from numerical study), when loaded simultaneously

The direction of tilt/rotation of footings on unreinforced soil is shown in figure 4.19 a-b and reinforced soil in figure 4.19 c for 50 mm wide footings, respectively. Therein it can be seen that the two adjacent footings rotate away from each other. This is due to the confinement effect of the foundation soil between the two footings due to load on the footings. The confinement effect makes the foundation soil in between the footings stronger and difficult to compress.



(b) (c)

Figure 4.19. Directions of tilt of two adjacent strip footings on unreinforced soil (a) schematic diagram showing tilt direction (b) S/B=1 on unreinforced soil (c) S/B=2 on reinforced soil, when loaded simultaneously

4.3. NUMERICAL ANALYSIS OF ADJACENT STRIP FOOTINGS

Numerical studies are conducted in the case of two footings loaded sequentially and three footings loaded simultaneously. Effects on stresses in foundation soil; bearing capacities and tilts of footings are being investigated. Parameters varied in this study are (i) Number of footings (ii) Types of loading conditions (iii) Clear spacing between the footings and (iv) Number of reinforcement layers in foundation soil.

The numerical studies are made on the behaviour of two adjacent strip footings on unreinforced (GB) and reinforced granular bed (RGB) overlying clay with/without voids. The influence of different parameters such as granular bed thickness, length of reinforcement/s, number of layers of reinforcement, presence of void/s beneath the footing/s in the weak soil etc…, on the behaviour of footings are carried out.

4.3.1. Numerical Studies of Adjacent Strip Footings on Unreinforced and Reinforced Medium Dense Sands

4.3.1.1. Two Footings Loaded Sequentially

(i) Variation of interference factor of bearing capacity (IF_2) with spacing between the footings

One of the footings representing the existing/old foundation is loaded with half of the estimated failure load of isolated footing and other footing loaded up to failure. The footings are loaded unequally and sequentially to simulate old and new footings. The property boundary line is assumed to be midway between the two footings. Geogrid reinforcement layers beneath the new footing are also considered to be extending equally beyond the footing on either side, only up to the property line. Analyses are performed on reinforced soil with reinforcement placed in one layer, two layers and three layers on S/B=2. Both unreinforced and reinforced sands are considered beneath the new footing for analyses.

To quantify the effect of old footing on the ultimate bearing capacity of new footing, the interference factor for new footing is determined. The interference factor for new footing IF_2 is defined in Equation 4.6.

$$\mathrm{IF_2} = \frac{\text{Ultimate load carrying capacity of the new footing in presence of old footing}}{\text{Ultimate load carrying capacity of single independent strip footing}} \quad (4.6)$$

Variation of bearing capacity of new footing adjacent to old footing follows a similar pattern as that of loading condition1(both the footing loaded simultaneously). Interference factor, $\mathrm{IF_2}$ increases with the spacing between the footings up to 2B and then decreases as spacing increases beyond 2B (Figure 4.20).

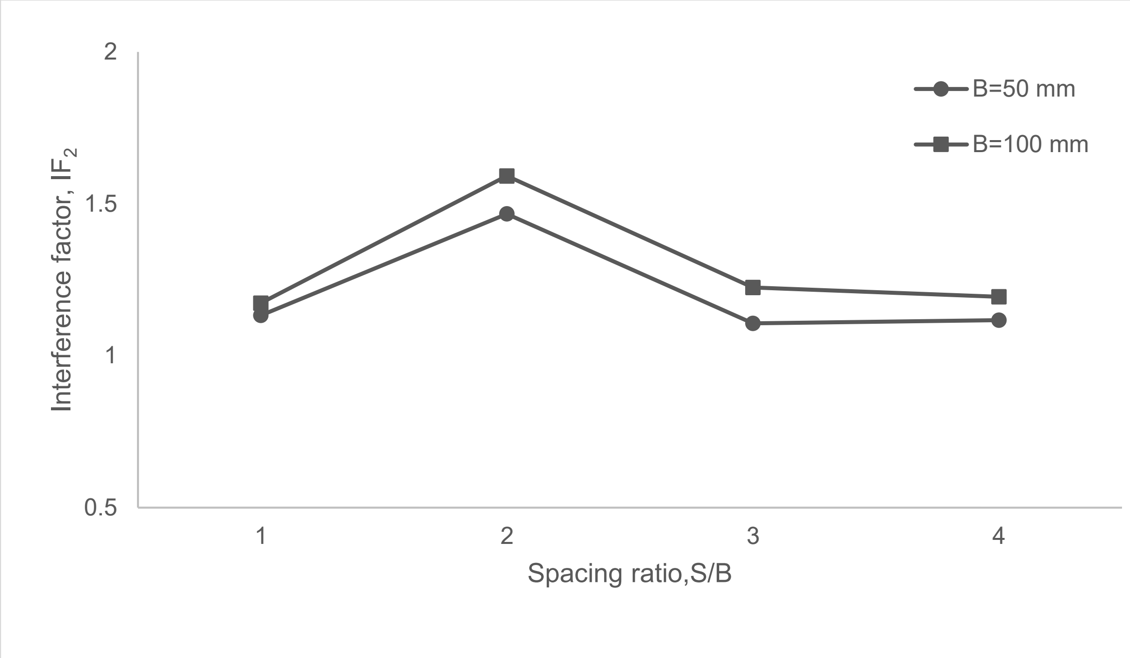


Figure 4.20. Variation of interference factor of bearing capacity (IF_2) with spacing ratio, S/B, for footing widths of 50 mm and 100 mm, on unreinforced foundation soil, (from numerical study)- when loaded sequentially

ii) Increase in confining pressure due to interference

The confining pressure developed due to interference is studied by variation in horizontal pressure, $\log_{10}\sigma'_{xx}$ at midway between the footings with the settlement of footing at 0.5B distance below the surface. The results are presented, as shown in figure 4.21. The soil beneath the old footing would have moved out sidewards. The soil beneath the subsequently loaded new footing also moves sidewards and causes an increase in confining pressure of soil between the footings, but not to the same extent as when footings are loaded simultaneously. Here again, confining pressure is maximum when S/B is about 1 (Figure 4.21).

The confining pressure remains constant after peaking in the case of S/B=3 and 4 for both types of loadings (Figures 4.5, 4.21). At S/B=2, the footings carry the maximum load (Figures 4.3, 4.20) for both types of loadings. However, in the case of simultaneous loading, for S/B=2, the confining pressure becomes asymptotic after undergoing about 15% strain. In the case of sequential loading, for S/B=2, it shows more of a brittle behaviour and also shows a reversal of strain. This could be due to a tendency of the densified sand in between the footings to dilate and try to ground heave.

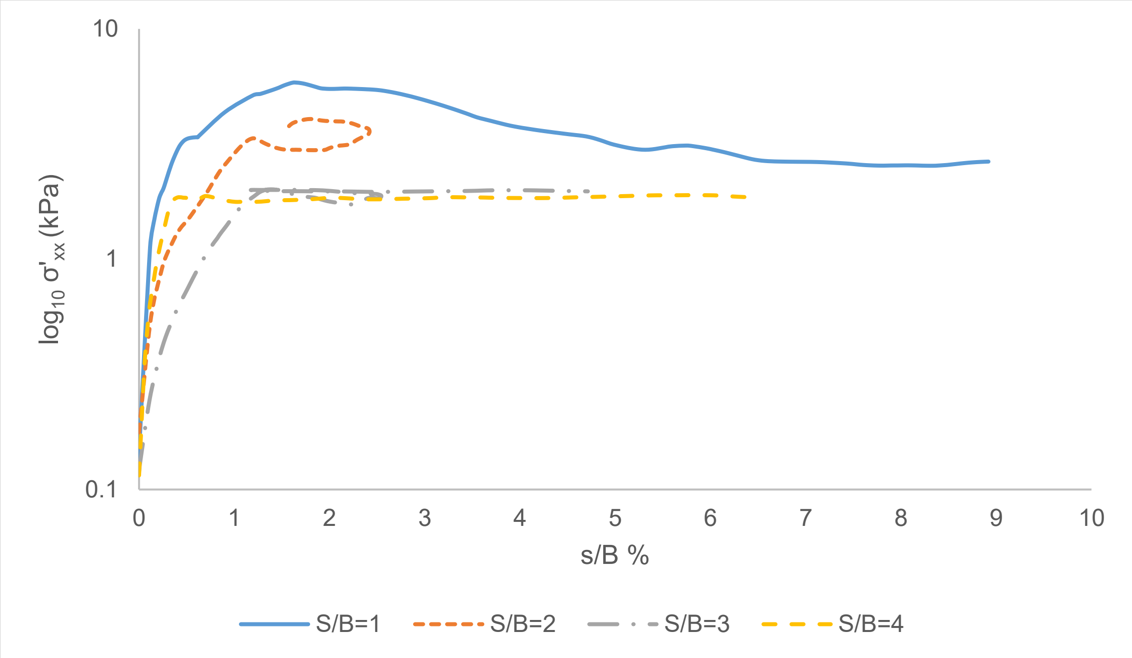


Figure 4.21. Variation of confining pressure σ'$_{xx}$ (midway between two footings at depth 0.5B below the surface) v/s normalised settlement of footing for footing width of 50 mm

4.3.1.2. Interference Effect on the Tilt of Footings

The tilt of footings on unreinforced and reinforced soils (reinforcement beneath the new footing only) are also being studied numerically for sequential loading case. Tilt is plotted against the spacing ratio, S/B for unreinforced soil for different footing widths (50 mm and 100 mm). Tilt is observed to decrease with an increase in spacing between the footings (Figure 4.22). In the case of new footing on reinforced soil, tilt is plotted against the number of reinforcement layers for the two footing widths (50 mm and 100 mm) (Figure 4.23). The tilt of the old footing is found to be increased when there is reinforcement beneath the new footing. Tilt increases with an increase in the number of layers of reinforcement. This is because the reinforced soil beneath the footing is stiffer. We have seen earlier that in the case of wider footings tilt is larger. The tilt of footing, when loaded sequentially and unequally, on unreinforced soil are observed to follow a similar trend as that reported by Salampatoor et al. (2019).

The direction of tilt is shown in figure 4.24 (along with computer outputs). CD represents the new strip footing, and EF represents the old/already existing strip footing (Figure 4.24 b-c). Both footings are tilting in the same anticlockwise direction, as seen in figure 4.24 b-c. For the old/existing footing, in the initial stages, increased stresses in the soil between the footings must have caused it to rotate anticlockwise or inward. The soil beneath the old footing would have already moved out sidewards before the construction of the new footing, and will not have any significant movement after the construction of adjacent new footing. But in the case of the new footing, as it is gradually loaded, the soil between the footings gets more and more confined, and makes it hard for the inner edge (D) of the new footing to compress, whereas the outer edge which is having lesser confinement effect undergoes larger settlements thus resulting in anticlockwise rotation or tilt. So, after the construction of the new footing, it is the soil beneath the new footing which has significant sideward movement. This causes an increase in confining pressure of soil between the footings, but not to the same extent as when footings are loaded simultaneously. Although there is an increase in stress in soil between the footings due to stress overlap, the confinement effect seems to dominate and dictate the direction of tilt.

In the case of reinforcement beneath new strip footing, larger load and stiffer foundation soil must have made it undergo larger and somewhat uniform settlements (compared to already existing footing). This will cause larger rotation of the old strip footing when the new strip footing is on reinforced soil.

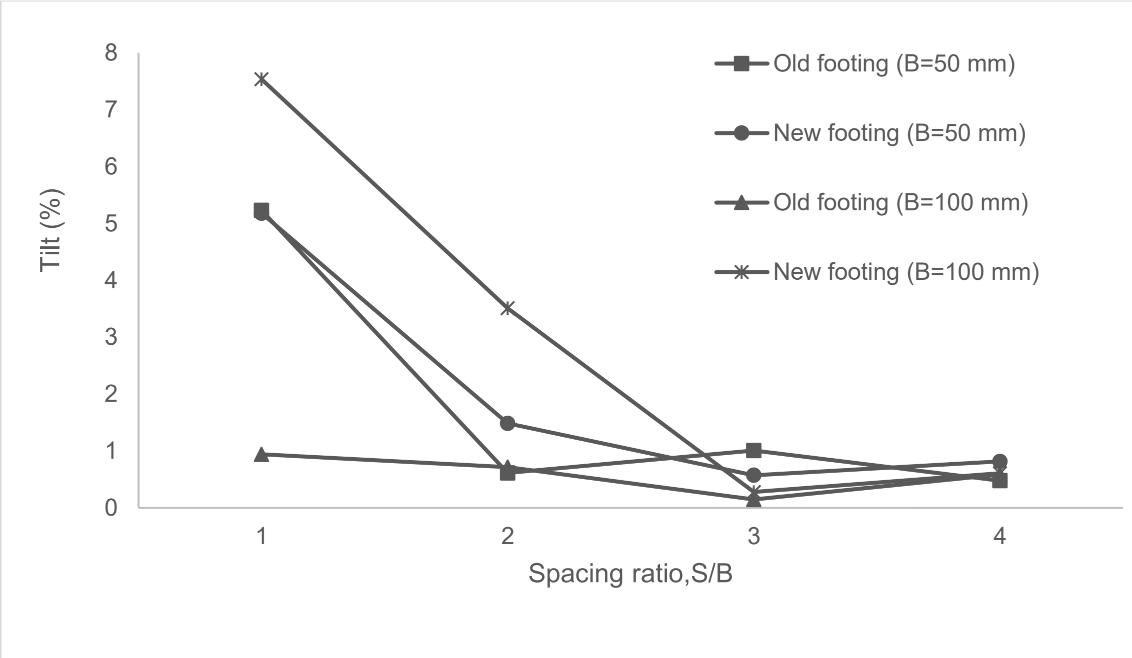


Figure 4.22. Tilt of old and new footing versus spacing ratio, S/B, for unreinforced soil conditions for footing widths of 50 and 100 mm (from numerical study), when loaded sequentially

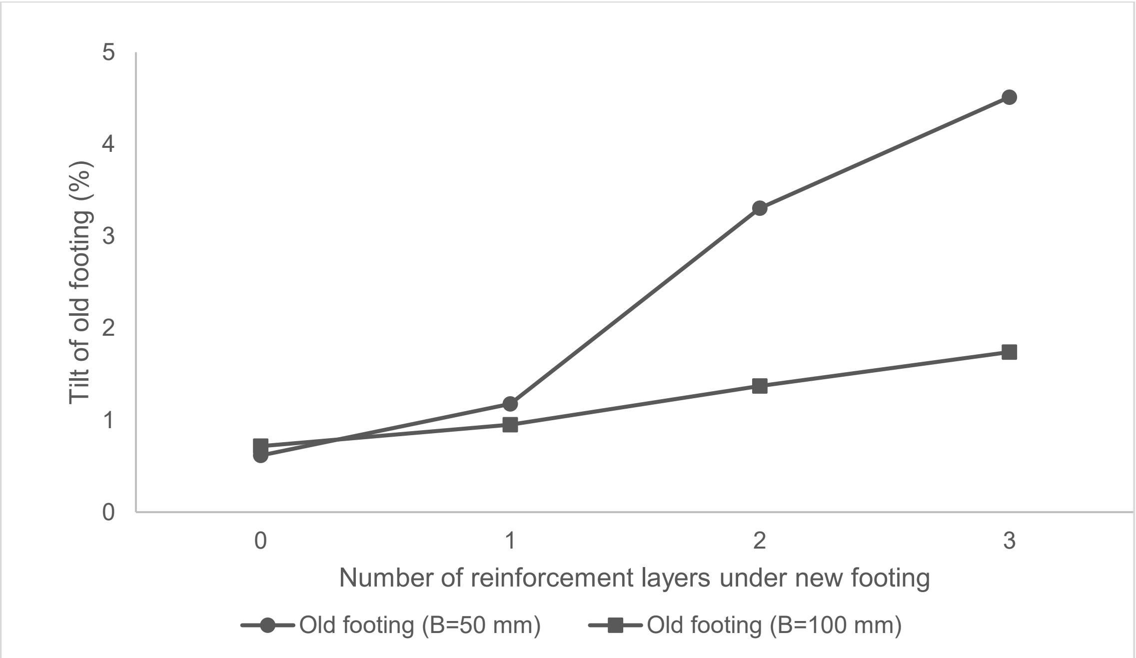
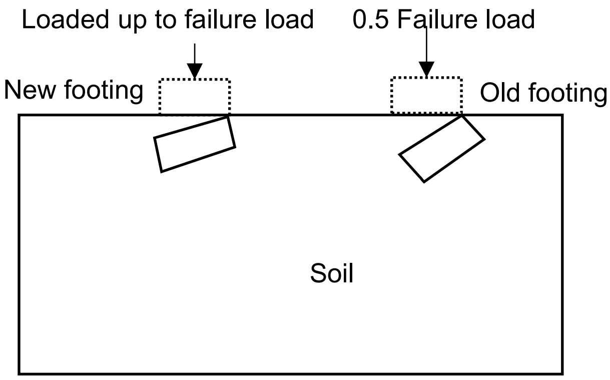
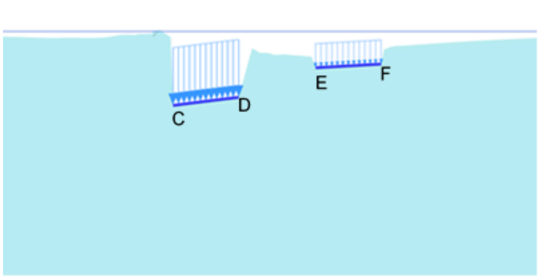
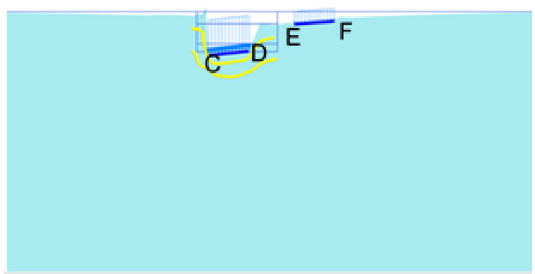


Figure 4.23. Tilt of old footing versus number of reinforcement layers under new footing for footing widths of 50 mm and 100 mm (for S/B=2, from numerical study)- when loaded sequentially



(a)



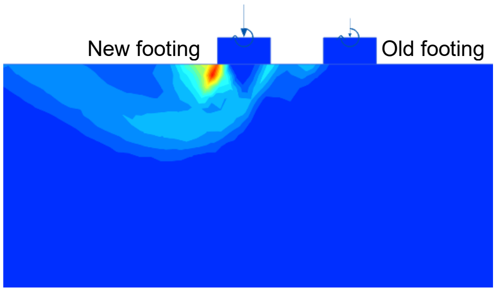


(b) S/B=2 (c) S/B=2

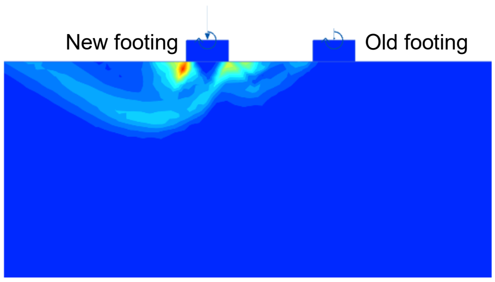
Figure 4.24. Directions of tilt of two adjacent strip footings (a) schematic diagram showing the direction of tilt (b) unreinforced soil (S/B=2) and (c) new footing is on reinforced soil (for S/B=2) for footing widths of 50 mm (from numerical study)-when loaded sequentially (Figures are not in the same scale)

4.3.1.3. Study of the Failure Surfaces

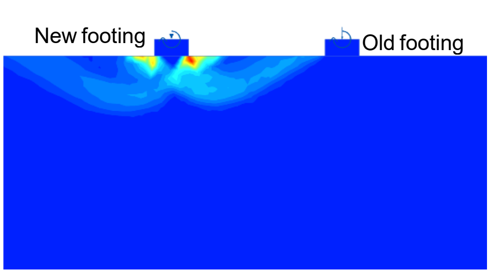
The elastic zones, as envisaged in Terzaghi's (1943) or Meyerhof's (1963) analyses, beneath old/already existing footings at all spacings of two adjacent footings on sands, is not very clear. One of the footings representing the existing/old foundation is loaded with half of the estimated failure load of isolated footing and other footing loaded up to failure. Only the new footing is loaded up to failure, and the already existing old footing is considered to be loaded to 50% capacity. Therefore, it is to be expected that the failure surfaces are fully or better developed in the case of new footings but certainly influenced by the presence of the already existing and loaded (up to 50%) old footings. The incremental shear strain contour pattern beneath the strip footings are shown in figure 4.25. At unreinforced soil conditions, failure surface from beneath the new footing is developed fully. When the new footing is provided with layers of reinforcement, the failure surface is seen to get wider and deeper (Figure 4.26).



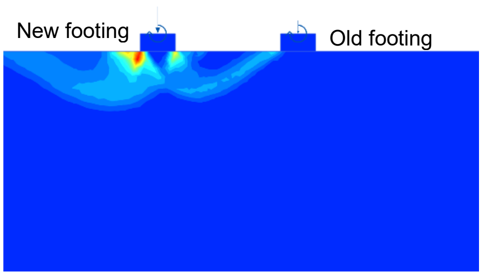
(a) S/B=1



(b) S/B=2



(c) S/B=3



(d) S/B=4

Figure 4.25. Incremental shear strain contour in the case of 50 mm wide footing, when loaded sequentially, for two adjacent strip footings with S/B=1, 2, 3, 4 on unreinforced soil

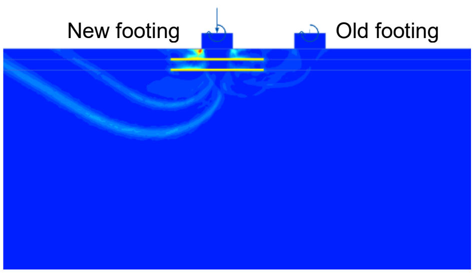


Figure 4.26. Incremental shear strain contour in the case of 50 mm wide footing, when loaded sequentially, for two adjacent strip footings with S/B=2 on reinforced soil (R=2), where R stands for the number of layers of reinforcement

4.3.2. Effect of Interference when Three Footings are Closely Spaced

The interference effect of closely spaced and simultaneously loaded three-strip footings on unreinforced soil at different spacings (S/B=1, 2, 3) is studied numerically for a footing width of 50 mm. The footing at the middle is under the interference effect from both the footings on either side. Bearing capacity behaviours of both middle footing and outer footing are being studied. Figure 4.27 shows the bearing pressure-normalised settlement curves of three-strip footings of the width of 50 mm that are placed together on unreinforced soil from the numerical study. Bearing capacity is observed to be more for central footing compared to outer footing for three footing case in all spacing ratios. The interference factor of bearing capacity for three footing case is the ratio of the ultimate load-carrying capacity of the footing in question in the presence of adjacent footings to that of the ultimate load-carrying capacity of single independent strip footing (same as that in Equation 4.1). Variation of the interference factor of the central footing to spacing ratio is plotted (Figure 4.28). From figure 4.28, it can be inferred that the effect of interference is greatest at S/B=1 and less at S/B=3 in the case of three footings. The bearing capacity of multiple strip footings on unreinforced soil are observed to follow a similar trend as that reported by Kumar and Bhoi (2008). The bearing capacity increases with a decrease in spacing between the footings. Kumar and Bhattacharya (2010) from the theoretical study, concluded that the interference factor of evenly spaced multiple strip footings is greater than one if S/B<3. Variation of tilt of central and outer footings in the case of three footing case are shown plotted in figure 4.29. It is found that the tilt of the centre footing is very less compared to outer footing.

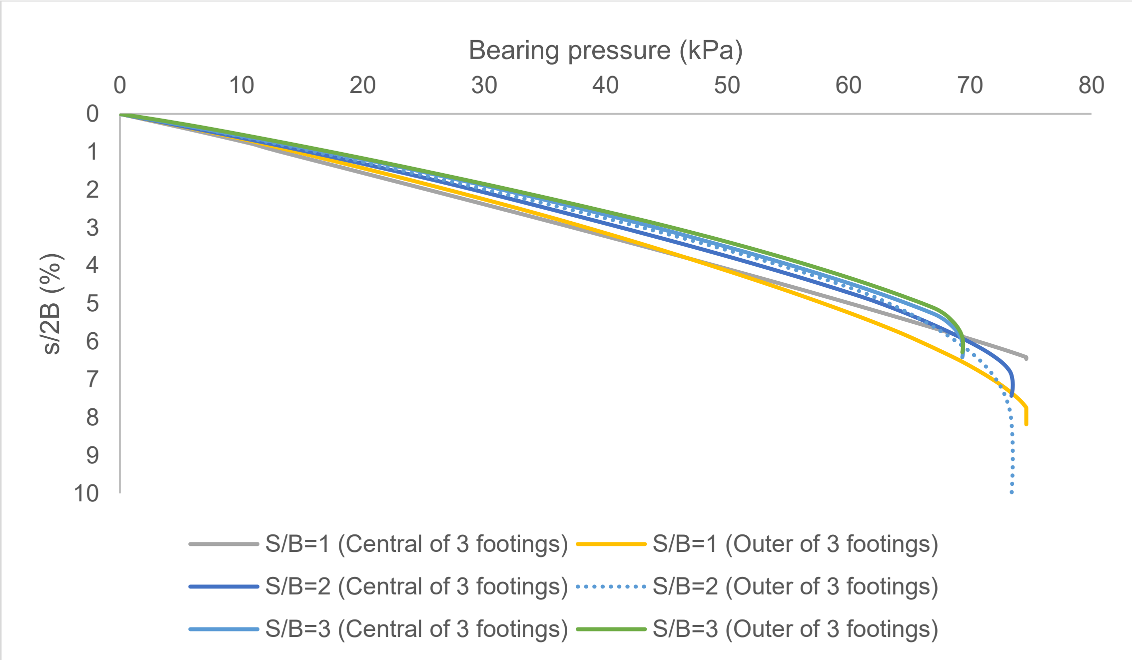


Figure 4.27. Bearing pressure-normalised settlement curves when three-strip footings each of width 50 mm are placed adjacent to each other on unreinforced soil (from numerical study)-when loaded simultaneously

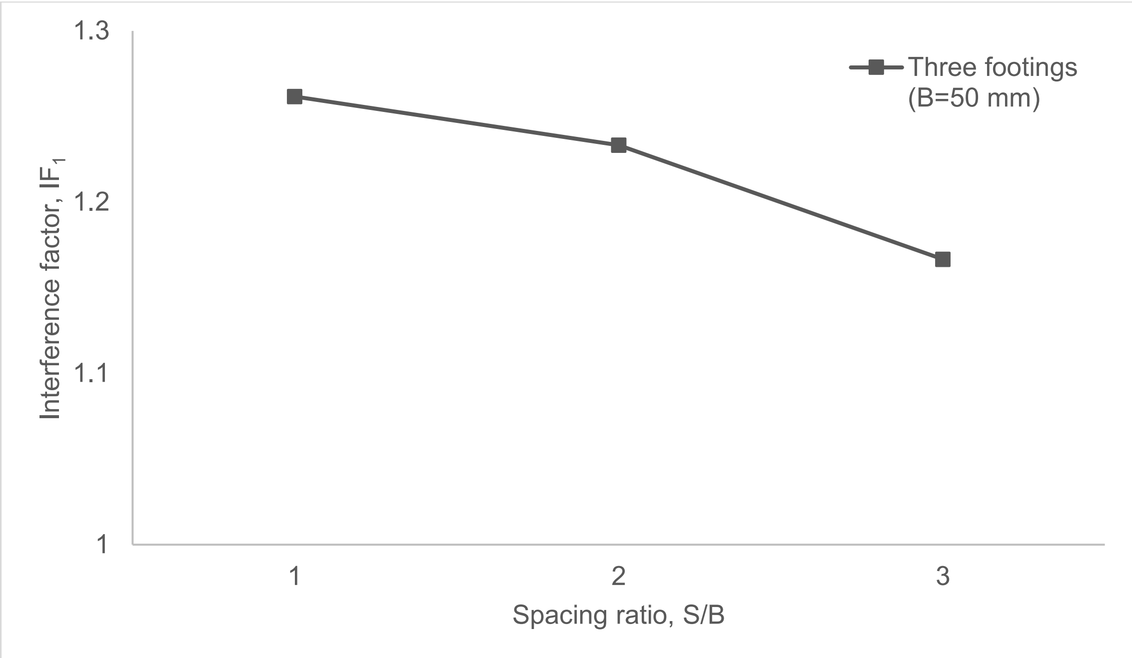


Figure 4.28. Variation of interference factor of bearing capacity (IF_1) of central footing when three-strip footings each of width 50 mm are placed adjacent to each other on unreinforced soil (from numerical study)- when loaded simultaneously

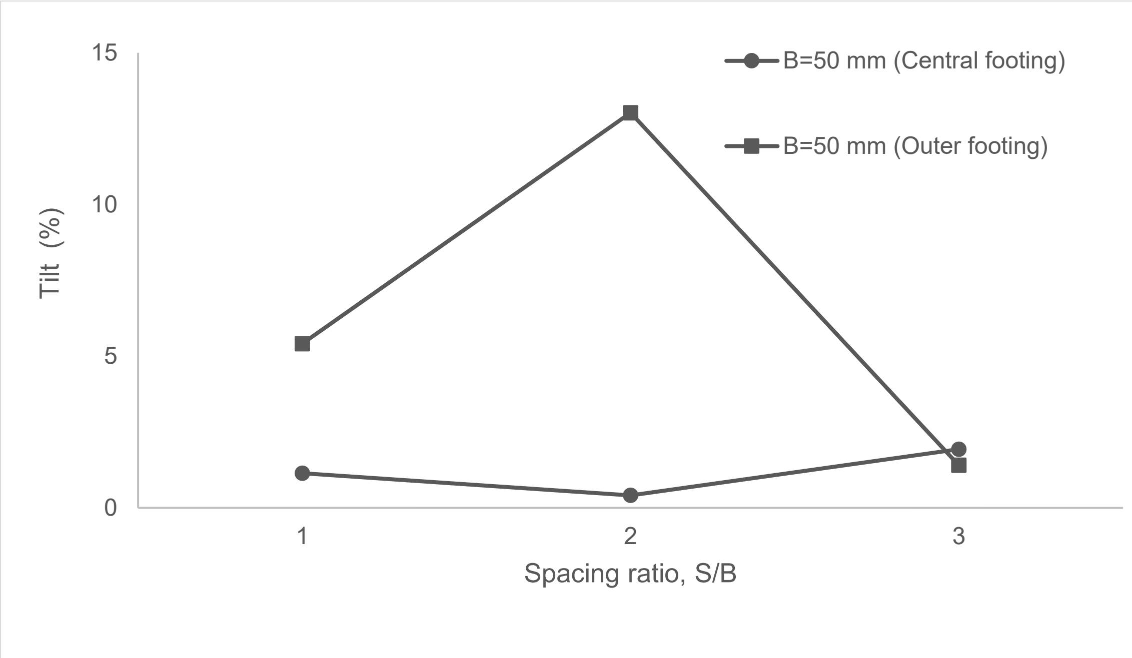


Figure 4.29. Tilt of central and outer footings versus spacing ratio, S/B, for the case of three footings on unreinforced soil conditions, for footing widths of 50mm (from numerical study)- when loaded simultaneously

4.3.3. Study on Behaviour of Two Adjacent Strip Footings on Granular Bed overlying clay with/without a Void

4.3.3.1. Single Strip Footing on Granular Bed Overlying Clay with/without Void

i) Effect of granular bed thickness

The bearing pressure vs normalised settlement relationship for 1m wide single strip footing on clay (H/B=0) as well as the granular bed (GB) overlying clay (H/B=0.75 to 2.0) are presented in figure 4.30. In the case of a strip footing resting on clay, the load-settlement curve peaks and becomes asymptotic. It shows the lowest bearing capacity among all the cases studied. In the case of H/B=0.75 and H/B=1 also, the response is similar, i.e., load settlement curve peaks and becomes asymptotic. However, with H/B=1.5, 2.0 and ∞, there is no peak up to about 4% strain and loads carried are significantly higher. At H/B=2 maximum improved bearing capacity is obtained. Figure 4.31 shows a comparison between bearing capacities obtained by numerical analyses from this study and theoretical bearing capacities as obtained by the approach suggested by Meyerhof and Hanna (1978). Ultimate bearing capacities are taken as peak values.

Whenever the curves had not peaked ultimate bearing capacities are obtained by the tangential intersection of load settlement curves. When there is no void, the magnitude of ultimate bearing capacity, q_u increases with an increase in H/B ratio up to a maximum and then remains constant (Okamura et al. 1997). In the present study, the optimum thickness of the granular bed is at H/B=2. Beyond H/B=2, there is not much increase in bearing capacity (Figure 4.31). When there is a void beneath the footing bearing capacity is significantly reduced, as seen in figure 4.31. At H/B=2, the failure surface at ultimate load is seen to be entirely located in the top granular bed (Figure 4.32). Thus, when H/B < H_{opt}/B, the failure surface goes beyond the upper sand layer into the clay layer beneath. However, when H/B ≥ H_{opt}/B, the failure surface at ultimate load is entirely located in the top sand layer (Das et al. 1993).

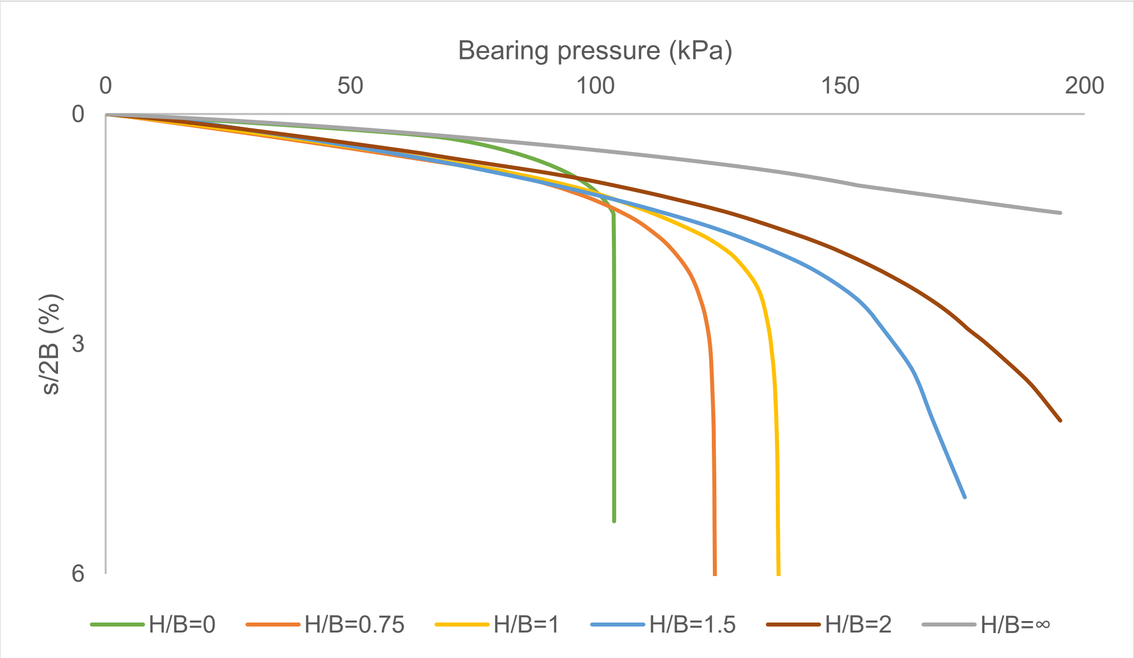


Figure 4.30. Bearing pressure-normalised settlement curves for single strip footing on GB over weak soil without void with 1 m wide strip footing

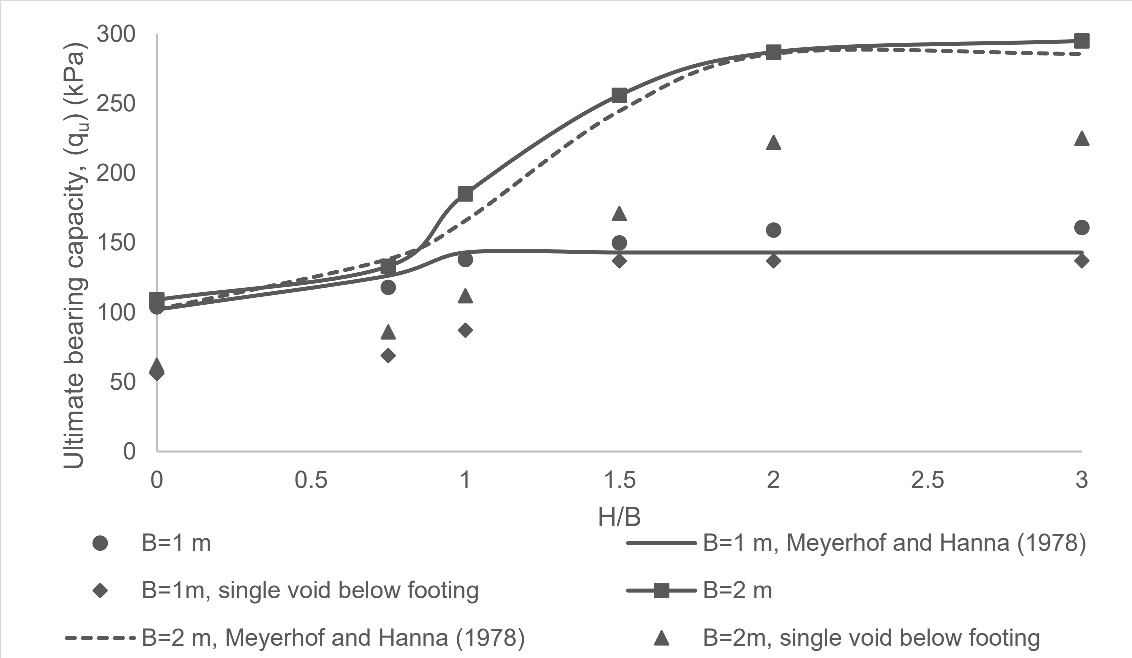


Figure 4.31. Variation of the bearing capacity with the thickness of granular bed H/B, for single strip footing on GB over clay with and without void

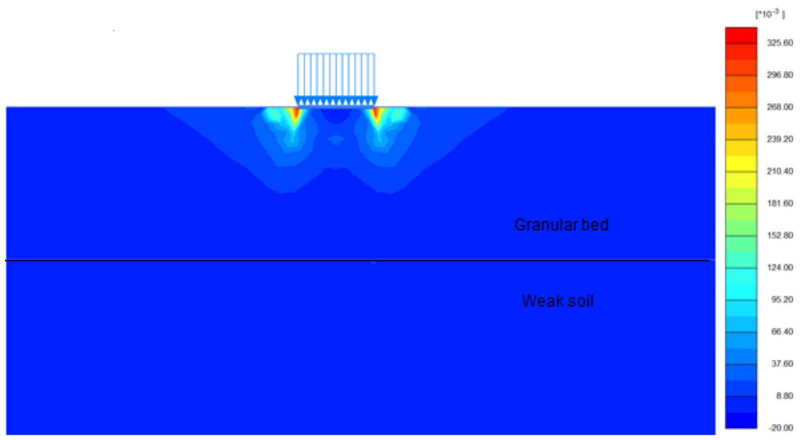


Figure 4.32. Failure of single strip footing on GB (H/B=2) over clay without void from the present study (with 2 m wide strip footing)

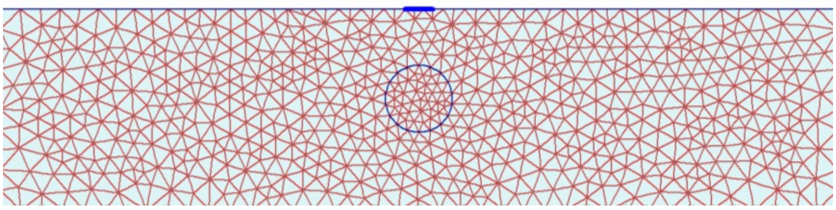
ii) Effect of footing width

From figure 4.31, it is evident that the bearing capacity increases with an increase in footing width on layered soil in the same manner as on a homogeneous soil layer.

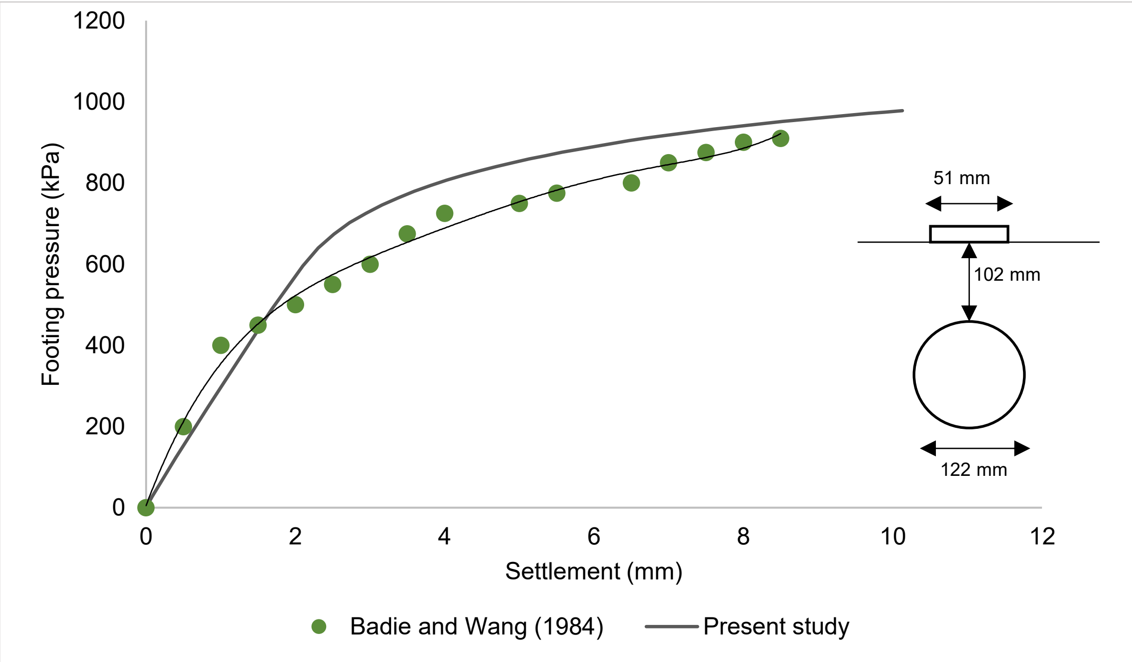
4.3.3.2. Granular Bed Overlying Clay with Void

i) Verification of the numerical model

To verify the validity of the present numerical approach, one of the case studies available in the literature by Badie and Wang (1984) has been used, and it is numerically simulated. Badie and Wang (1984) conducted some experiments to study the load-carrying capacity of a strip footing above a void. The experiments were conducted in a tank with dimensions 1524 mm length x 140 mm width x 366 mm height. A Kaolin clay with properties, Young's modulus of 19.87 MPa, unit weight of 16.28 kN/m^3, cohesion of 158.7 kPa and friction angle of 8^0 was used. Figure 4.33a shows the finite element mesh shape used in the validation study. Figure 4.33b shows a comparison of Badie and Wang's (1984) experimental results with the present numerical study. There is reasonably good agreement between the two results.



(a)



(b)

Figure 4.33. (a) Finite element mesh used in the present study for validation of experimental results of Badie and Wang (1984), (b) Comparison between the experimental results of Badie and Wang (1984) and present numerical study

4.3.3.3. Single Strip Footing on GB Overlying Weak Soil with A Void Below the Footing

The reduction factor, R, was used by Azam et al. (1991) to describe the effect of a void on the load-carrying capacity. The reduction factor is defined as $R=q_u'/q_u$, where q_u' and q_u are load-carrying capacity of the strip footing on the ground with a void and without a void respectively. Kiyosumi et al. (2007) also evaluated the effect of void using reduction factor in terms of yield pressure.

The effect of the void is also assessed in the present study, by reduction factor, RF-GB, which is defined in Equation 4.7.

$$\mathrm{RF-GB} = \frac{\text{Load carrying capacity of a strip footing on GB overlying weak soil with a void}}{\text{Load carrying capacity of a strip footing on GB overlying weak soil without a void}} \quad (4.7)$$

A continuous circular void of 0.5B diameter is considered to be placed below single strip footing on GB overlying weak soil. The void is located in the weak soil. Both eccentricities from the centerline of footing and depth from the surface are varied (X/B varied from 0 to 3.0, Y/B varied from 1.5 to 5.0) (Figure 3.13c). Maximum reduction in bearing capacity due to the effect of the void is noted when the void is located exactly below the footing, i.e., when X/B=0 and H/B=1 (Figure 4.34). Reduction factors increase as spacing (X and Y) increase. It is thus observed from figure 4.34 that the bearing capacity of a strip footing is affected by the position of the void. When the void is beyond X/B=3 from the centreline of the footing, the influence of the void becomes insignificant.

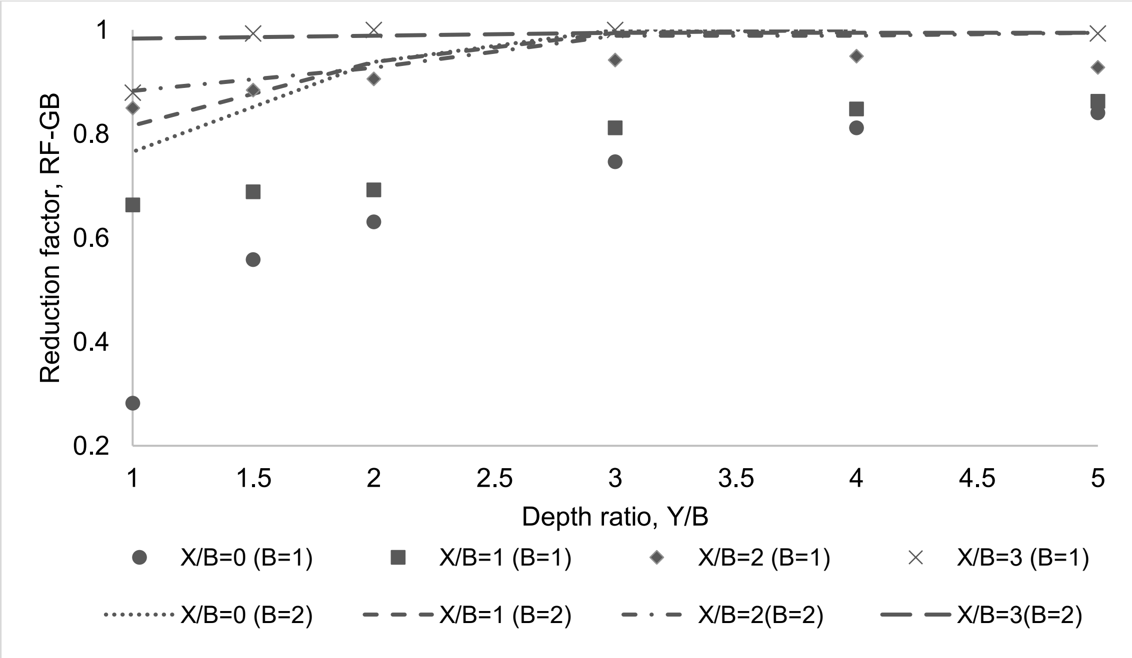


Figure 4.34. Variation of reduction factor, RF-GB, with depth ratio (Y/B) for varying X/B, for single void below single strip footing on GB overlying weak soil with void for B=1m and 2m (H/B=1)

4.3.3.4. Two Adjacent Strip Footings on Granular Bed Overlying Clay without Voids

i) Both the footings loaded simultaneously till failure

Bearing pressure-normalised settlement curves for two adjacently placed strip footings on GB overlying weak soil from the numerical study (with 1 m wide strip footing, H/B=1) are presented in figure 4.35. Maximum bearing capacity obtained for the spacing ratio S/B=1.5.

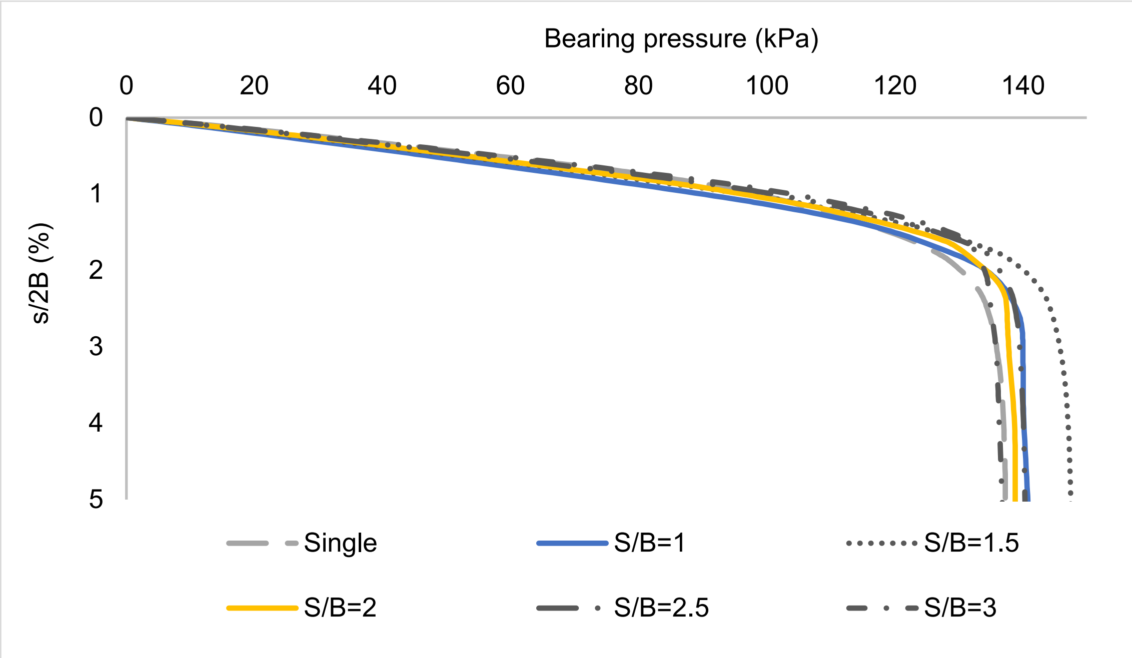


Figure 4.35. Bearing pressure-normalised settlement curves for two adjacently placed strip footings on GB overlying weak soil (with 1 m wide strip footing, H/B=1)

When two footings are placed adjacent to each other, there will be an 'interference effect'. To study the interference effect of two adjacent strip footings on granular bed overlying weak soil/clay analyses were performed for H/B ratios of 0.75,1.0 and 1.5. The spacing ratio, S/B values between the footings is varied as 1.0, 1.5, 2.0, 2.5 and 3.0. To study the effect of interference of two adjacently spaced strip footings on the bearing capacity of soil; the interference factor of bearing capacity (IF'_1) is determined in each case. The interference factor of bearing capacity (IF'_1) is defined as follows in Equation 4.8.

$$IF'_1 = \frac{\text{Load carrying capacity of the footing in the presence of an adjacent footing on GB overlying weak soil with no void}}{\text{Load carrying capacity of single independent strip footing on GB overlying weak soil with no void}} \tag{4.8}$$

Figure 4.36 shows the variation of interference factor of bearing capacity, IF'_1, with different spacing ratios (S/B values) between the footings varying from 1.0 to 3.0 for different H/B ratios. It can be noted that the interference factor is generally maximum at S/B=1.5, especially when the H/B ratio is 1.5. A similar trend is observed for a footing width of 2 m (Figure 4.37). S/B denotes non-dimensionally the spacing between the footings and H/B denotes non-dimensionally the thickness of the granular bed. For both 1m and 2m footing widths, the interference factor initially increases with the increase in spacing up to a maximum value and then decreases with the further increase in spacing. The spacing at which the maximum interference factor for bearing capacity is observed is considered as optimum spacing. In this case, 1.5B is obtained as optimum spacing. The interference factor value is also observed to increase with the increase in footing width (Figures 4.36 and 4.37). These results are similar to the results of some previous studies (Ghosh and Kumar 2011, Saha Roy and Deb 2019). Ghosh and Kumar (2011) conducted interference studies on cohesionless layered soil for strip footings and reported that maximum bearing capacity can be obtained at an optimum spacing between the footings. Saha Roy and Deb (2019) studied angular footings on layered soil and reported that interference factor initially increases with the increase in S/B ratio, and reaches the peak at optimum spacing. The interference factor decreases with a further increase in the S/B ratio and finally reaches a value of 1, meaning no more interference and footings act independently. Compared to strip footings on a homogeneous granular soil deposit (H/B=∞), two strip footings on the granular bed over a weak soil layer have a larger interference factor, especially when H/B=1.5. This is true for both footing widths (B=1m and 2m) studied in this research work.

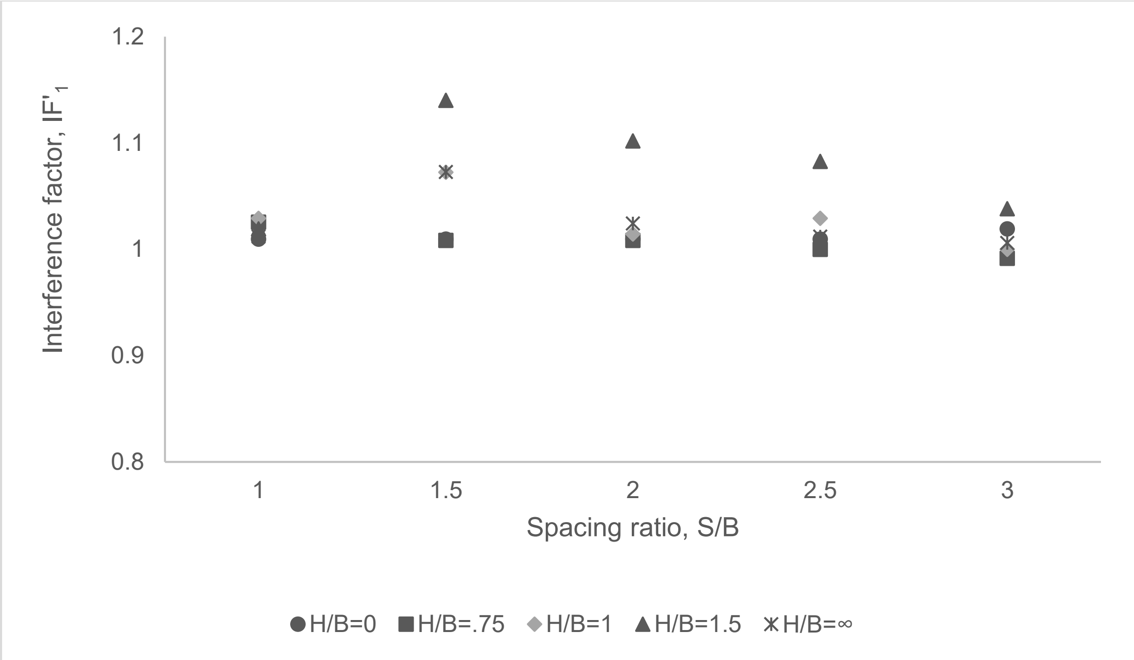


Figure 4.36. Variation of interference factor of bearing capacity (IF'_1) with spacing ratio, S/B, for footing width of 1 m, for different thickness of granular bed (H/B) overlying weak soil

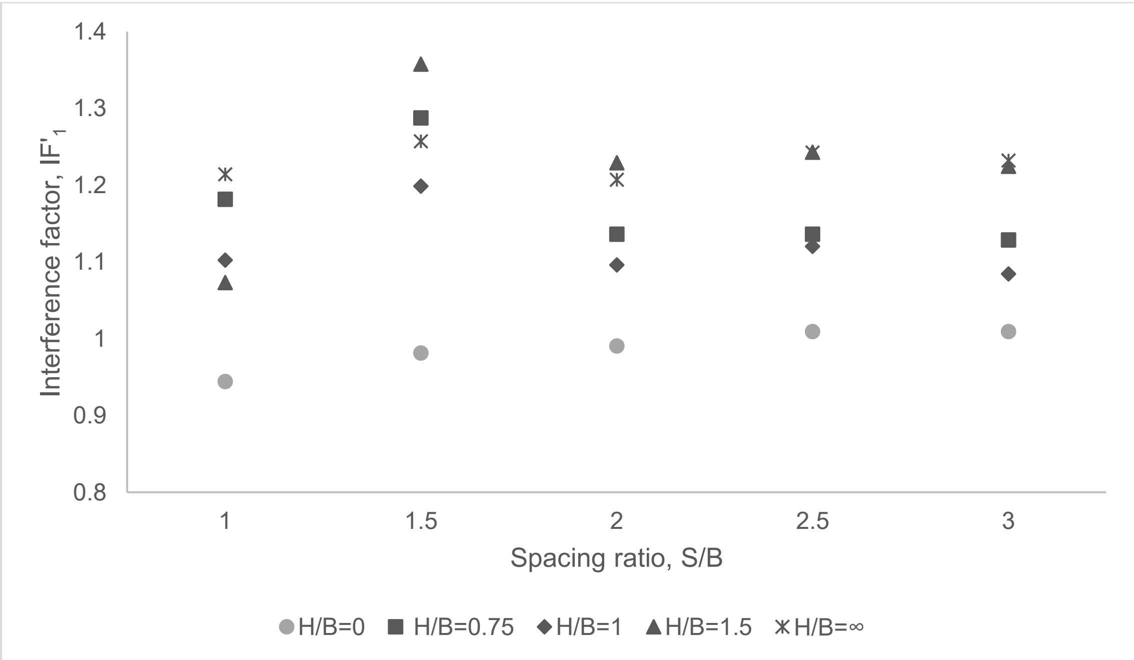


Figure 4.37. Variation of interference factor of bearing capacity (IF'_1) with spacing ratio, S/B, for footing width of 2 m, for different thickness of granular bed (H/B) overlying weak soil

ii) Both the footings loaded sequentially- Old footing loaded with half of the estimated failure load of single strip footing and adjacent new footing loaded up to failure

In the second loading condition, one of the strip footings representing an already existing foundation is loaded with half of the estimated failure load of single strip footing, and adjacent new strip footing loaded up to failure. To study the effect of interference of such two adjacently spaced strip footings on granular bed overlying clay loaded sequentially, interference factor of bearing capacity (IF'_2) is determined in each case. The interference factor of bearing capacity of new footing in the presence of old footing (IF'_2) is defined as follows in Equation 4.9. For both 1m and 2m footing widths, the interference factor initially increases with the increase in spacing up to a maximum value and then tends to decrease with the further increase in spacing (Figure 4.38). But the variation of interference factor to spacing ratio is different compared to loading condition 1(both footings loaded simultaneously). The interference factor is seen to peak at a much higher S/B ratio. Figure 4.38 shows the variation of interference factor of bearing capacity, IF'_2 with different spacing ratios (S/B values) between the footings varying from 1.0 to 3.0 for different H/B ratios.

$$IF'_2 = \frac{\begin{array}{c}\text{Load carrying capacity of the new footing in the presence of an adjacent old footing}\\ \text{(loaded to half its ultimate capacity) on GB overlying weak soil with no void}\end{array}}{\begin{array}{c}\text{Load carrying capacity of single independent strip footing}\\ \text{on GB overlying weak soil with no void}\end{array}} \quad (4.9)$$

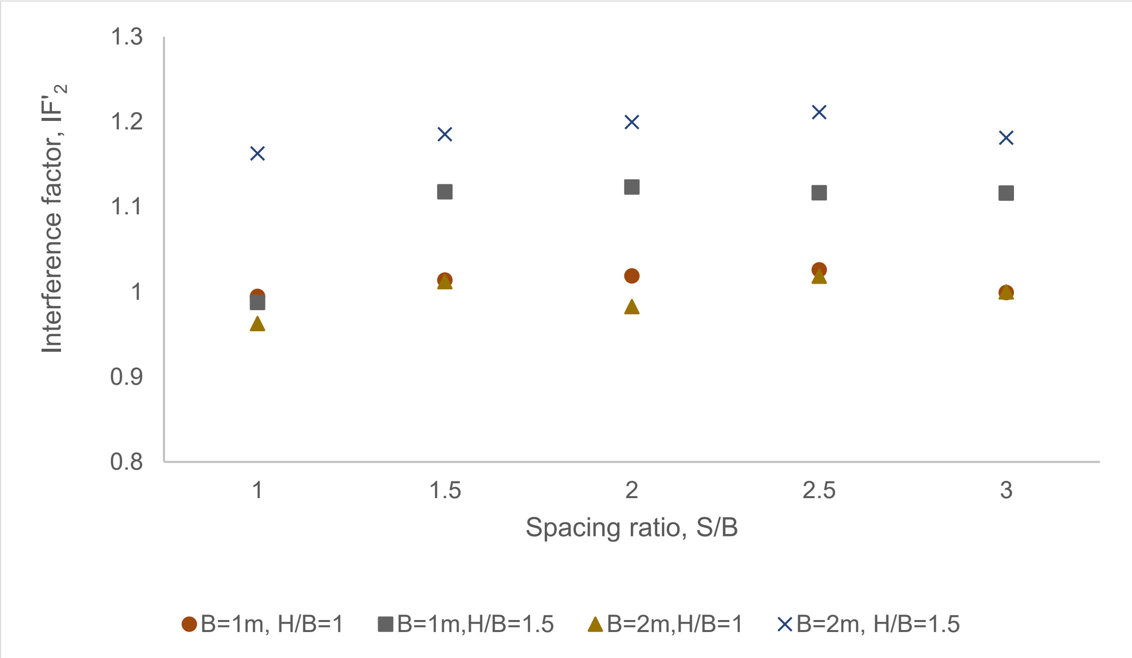


Figure 4.38. Variation of interference factor of bearing capacity of new footing (IF'_2) with spacing ratio, S/B, for footing widths of 1 and 2 m, for different thickness of granular bed (H/B) overlying weak soil for sequential loading

4.3.3.5. Two Adjacent Strip Footings on Granular Bed Overlying Weak Soil with A Single Void

i) Both the footings loaded simultaneously up to failure

Two adjacently placed strip footings are considered on the surface of GB overlying weak soil with a void. The void is considered to be circular of diameter 0.5B, where B is the width of the footing and void is considered at the interface between the granular bed and weak soil. The single void is considered in different positions, such as below the centre of one of the footing (Figure 3.15a) and the midpoint between the footings (Figure 3.15b). To study the effect of the influence of two closely placed strip footings loaded simultaneously on GB overlying weak soil with the void, on the bearing capacity, influence factor of bearing capacity with void (IF_{v1}) is determined in each case. The influence factor of bearing capacity with the void is defined as follows in Equation 4.10.

$$IF_{V1} = \frac{\text{Load carrying capacity of one of the footing in the presence of an adjacent footing on GB overlying weak soil with void}}{\text{Load carrying capacity of single independent strip footing on GB overlying weak soil with no void}} \quad (4.10)$$

Figure 4.39 shows the variation of IF_{v1} with different spacing ratios (S/B values) between the footings varying from 1.0 to 3.0. Influence factor IF_{v1} is the combined effect of a void (reduction in bearing capacity due to the presence of void, reduction factor) and the interference phenomenon happening between the two strip footings. The formation of voids beneath footings reduces the load-carrying capacity of the footings. In the case of a single void under two footings, the maximum reduction in bearing capacity of footing reported when the void is formed directly below one of the footings as compared to the void present below the midpoint between the footings (Figure 4.39). With the void the influence factor IF_{v1} (Figure 4.37) are ranging between 0.6-0.9. Variation of spacing between 1B-3B does not seem to make any significant difference.

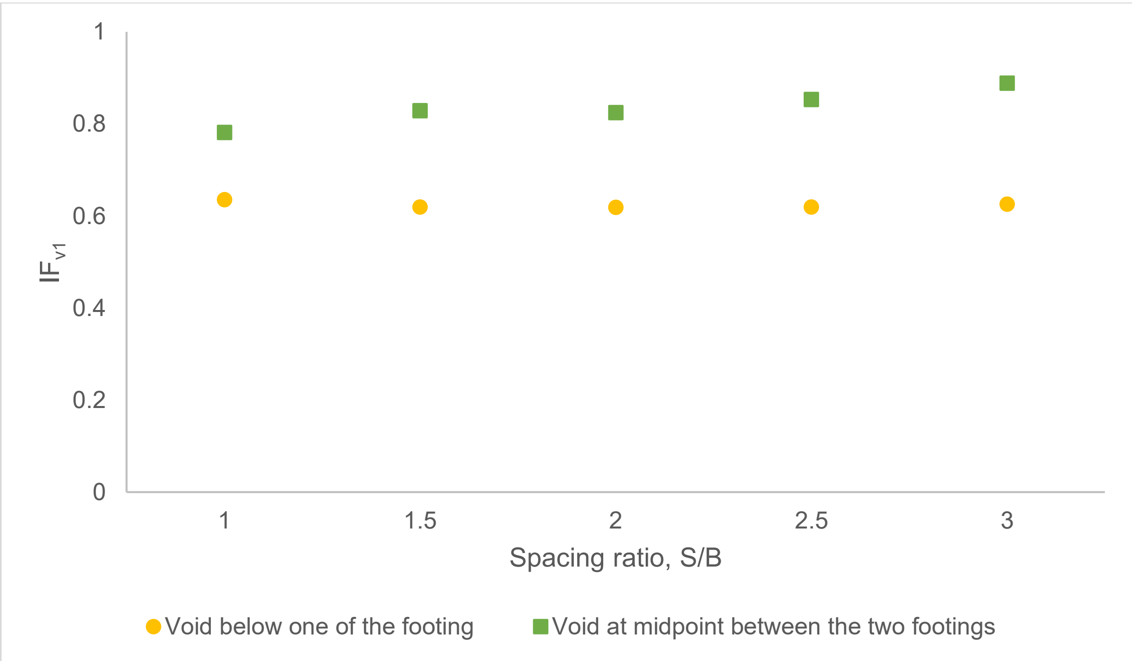


Figure 4.39. Variation of influence factor (IF_{v1}) with spacing ratio, S/B, for footing width of 2 m, H/B=1 for granular bed overlying weak soil with void for simultaneous loading

ii) Old footing loaded with half of the estimated failure load of single strip footing and adjacent new footing loaded to failure with void (sequential loading)

Two adjacently placed strip footings are considered on the surface of GB overlying weak soil with a void. The void is considered to be circular of diameter 0.5B, where B is the width of the footing and void is considered at the interface between the granular bed and weak soil. The single void is considered in three different positions, such as below the centre of old footing, below the centre of new footing, and midpoint between the two footings (Figures 3.16 a-c). In order to study the effect of interference of two closely placed strip footings sequentially loaded on GB overlying weak soil with the void, on the bearing capacity, influence factor of bearing capacity with void (IF_{v2}) is determined in each case. The influence factor of bearing capacity with void (IF_{v2}) is defined as follows in Equation 4.11.

$$IF_{V2} = \frac{\text{Load carrying capacity of the new footing in the presence of an adjacent old footing (loaded to half its ultimate capacity) on GB overlying weak soil with void}}{\text{Load carrying capacity of single independent strip footing on GB overlying weak soil with no void}} \quad (4.11)$$

Figures 4.40-4.43 show the variation of IF_{v2} with different spacing ratios (S/B values) between the footings varying from 1.0 to 3.0 for different void positions. In the case of a single void under two footings, the maximum reduction in the bearing capacity of new footing is seen when a void is formed directly below the new footing. It is also seen that the influence values (IF_{v2} values) increase with an increase in the thickness of granular bed and also IF_{v2}values increase with an increase in the width of footings. Reduction in bearing capacity of new footing due to the presence of void (up to size/diameter of 0.5B) beneath the adjacent old footing is not very significant because the IF_{v2}values are nearly equal to 1 (Figures 4.40-4.43).

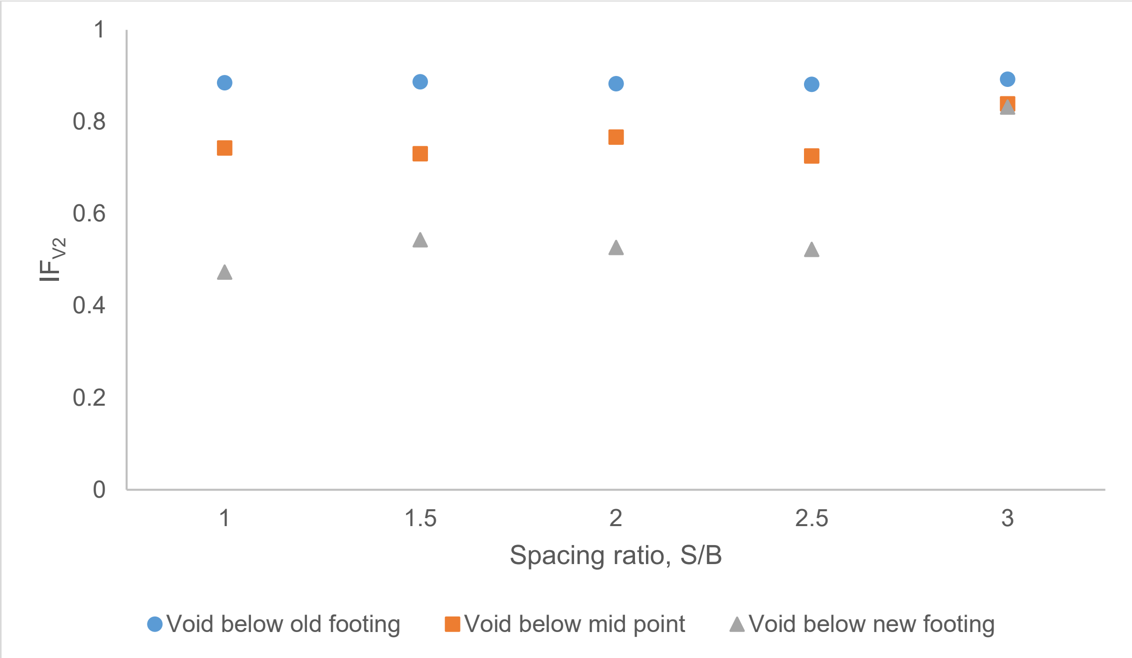


Figure 4.40. Variation of influence factor (IF_{v2}) with spacing ratio, S/B, for footing width of 1 m, for H/B=1 for granular bed overlying weak soil with void for sequential loading

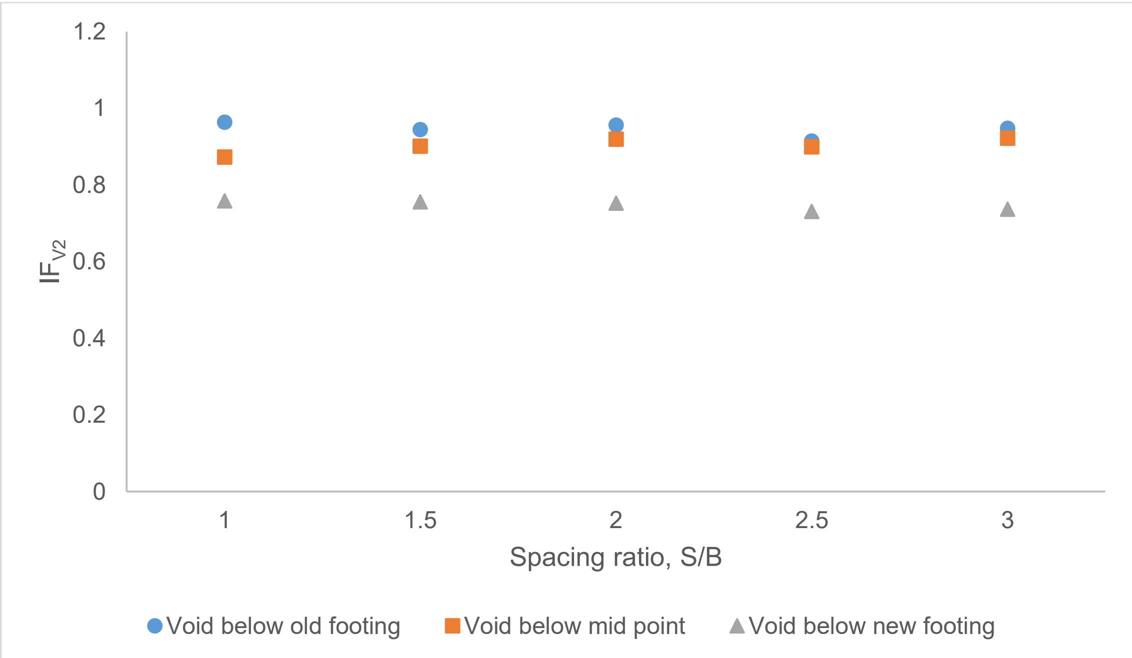


Figure 4.41. Variation of influence factor (IF_{v2}) with spacing ratio, S/B, for footing width of 1 m, for H/B=1.5 for granular bed overlying weak soil with void for sequential loading

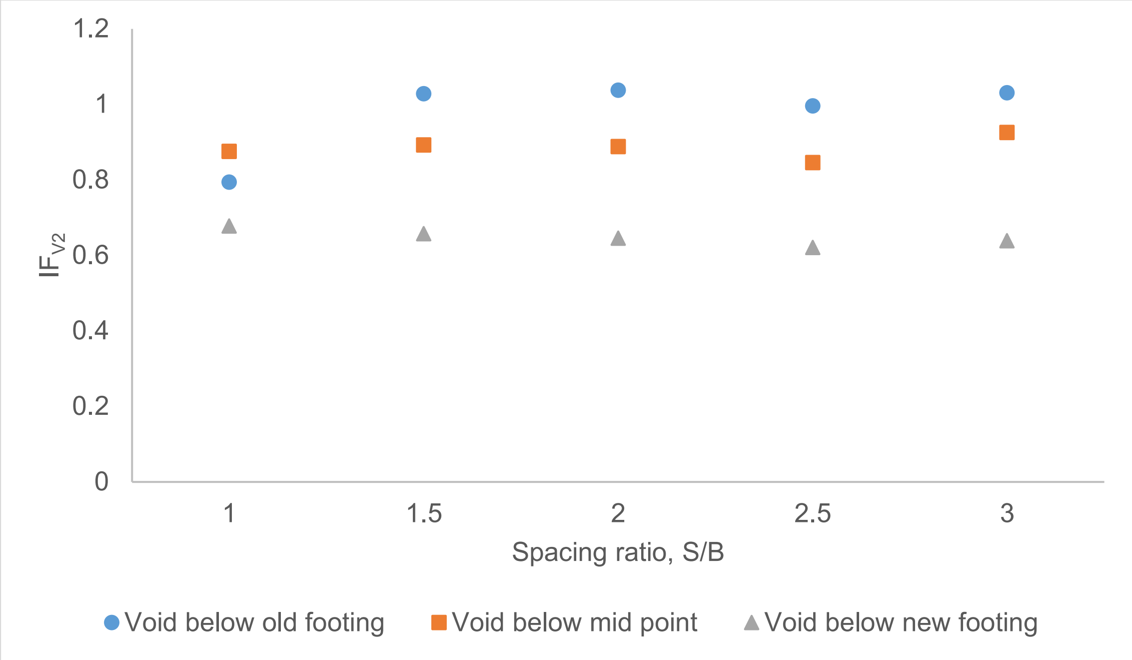


Figure 4.42. Variation of influence factor (IF_{v2}) with spacing ratio, S/B, for footing width of 2 m, H/B=1 for granular bed overlying weak soil with voids for sequential loading

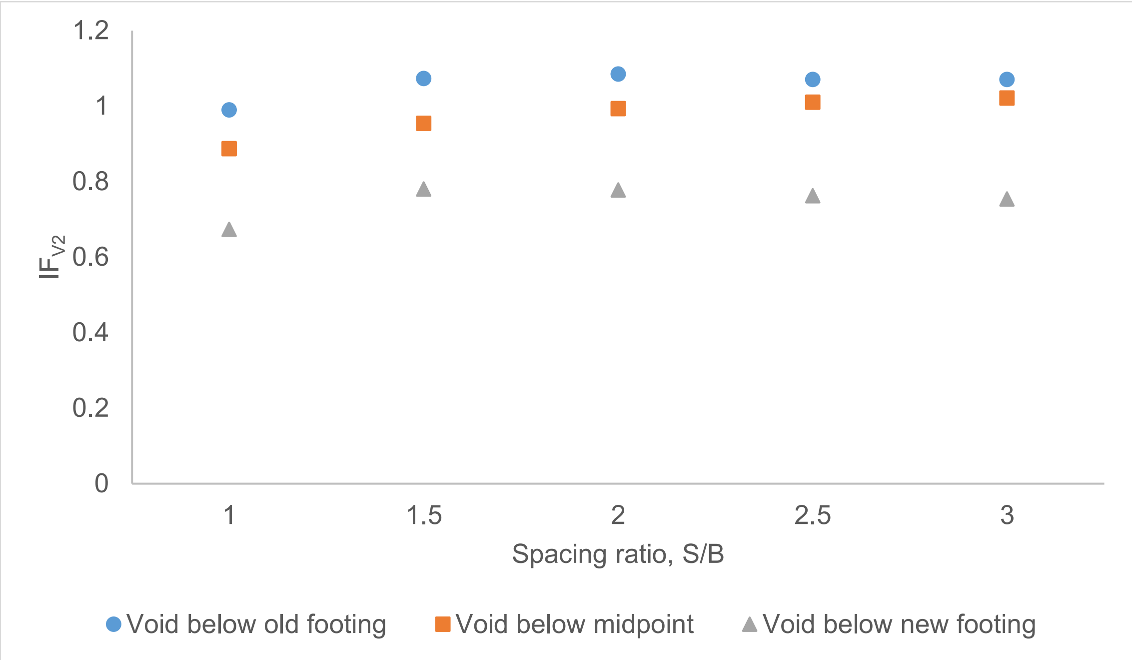


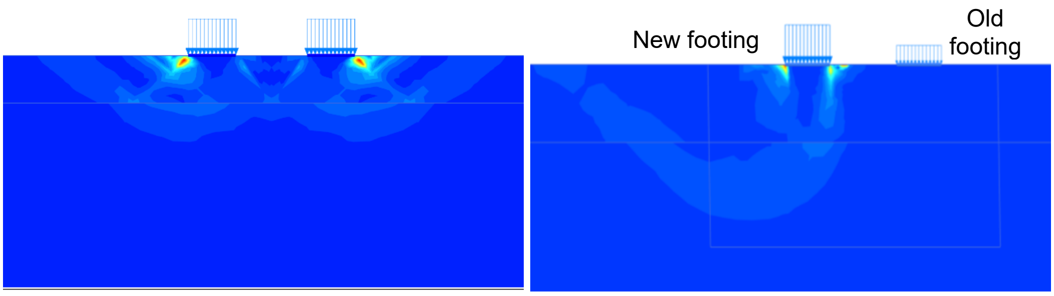
Figure 4.43. Variation of influence factor (IF_{v2}) with spacing ratio, S/B, for footing width of 2 m, for H/B=1.5 for granular bed overlying weak soil with voids for sequential loading

4.3.3.6. Study of the Failure Surfaces

The incremental shear strain contour patterns, for single and two adjacent strip footings on GB overlying weak soil, with and without void/s are shown in figures 4.44-4.47. When a void is formed in the weak soil at the interface, the failure surface developed from the nearest footing tends to move towards the void and is found to be narrower than the no void case. Two adjacent footings at spacing (S/B=1.5), on GB over voids case, with the void in between the footings, failure surface is seen connecting the two footings and the voids (Figures 4.46 b, 4.47 c). The critical failure mode is always formed through the weakest zone. The failure zone extends from the edge of the footing toward the nearest void, without forming an active wedge beneath the footing (Kiyosumi et al. 2007).

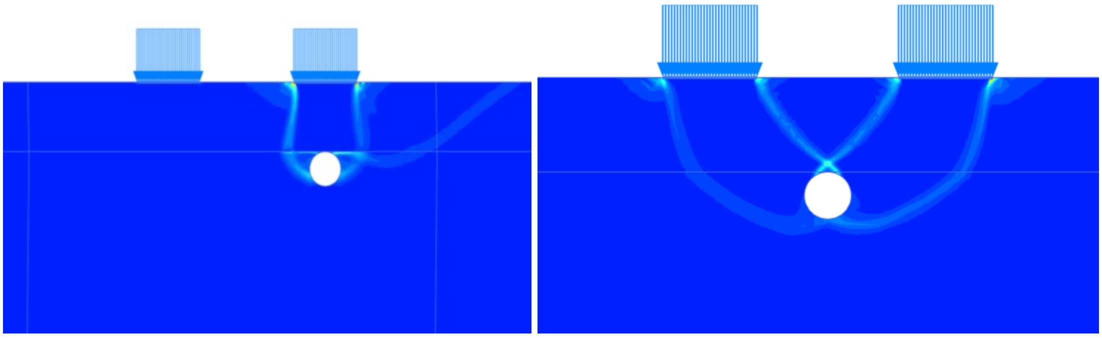
(a) (b)

Figure 4.44. Incremental shear strain contours of single strip footing on GB overlying weak soil for H/B=1, B=1m loaded to failure (a) without void (b) with void (X/B=0, Y/B=1.5)



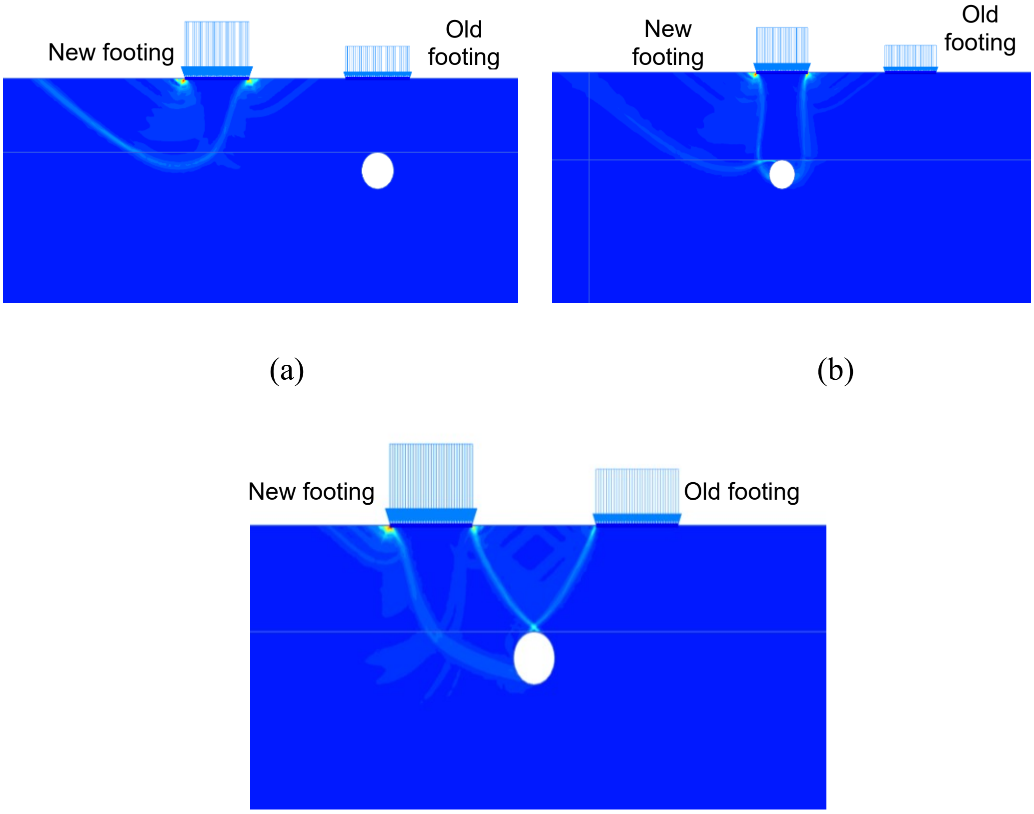
(a) (b)

Figure 4.45. Incremental shear strain contours of two adjacent strip footings with S/B=1.5 on GB overlying weak soil with no void for H/B=1 (a) simultaneously loaded to failure, B=1m (b) sequentially loaded, B=2m (old footing subjected to 50% failure load, new footing fully loaded)



(a) (b)

Figure 4.46. Incremental shear strain contours of two adjacent strip footings with S/B=1.5 on GB overlying weak soil for H/B=1, B=2m, simultaneously loaded to failure (a) void below one of the footings (b) void at midpoint between the two footings



(a) (b)

(c)

Figure 4.47. Incremental shear strain contours of two adjacent strip footings with S/B=1.5, B=1m on GB overlying weak soil with void at the interface between GB and weak soil, sequentially loaded (a) void below old footing, (H/B=1.5) (b) void below new footing, (H/B=1) (c) void at midpoint between the footings, (H/B=1) (old footing subjected to 50% failure load, new footing fully loaded)

4.3.4. Footing/s on Granular Bed (GB)/Reinforced Granular Bed (RGB) Overlying Clay without Voids

4.3.4.1. Single Strip Footing on Reinforced Granular Bed Overlying Clay without Voids

When single strip footings are placed on reinforced granular bed overlying clay, the bearing capacity increases due to the presence of the reinforcement layer. Bearing capacity also increases with the increase in the number of layers of reinforcement and width of footing. The bearing pressure-normalised settlement relationship for 1m and 2 m wide single strip footings on GB and RGB underlain by clay are presented in figure 4.48.

The increase in bearing capacity of any improved ground, as compared to the unimproved ground are quantified in terms of Bearing Capacity Ratio (BCR). In this context, Bearing Capacity Ratio (BCR) is defined as in Equation 4.12.

$$\mathrm{BCR} = \frac{\text{Load bearing capacity of footing on GB or RGB on clay}}{\text{Load bearing capacity of footing on clay}} \tag{4.12}$$

BCR increases with an increase in the number of reinforcement layers as shown in figure 4.49. The soil strength and its stiffness are increased by providing the reinforcements or inclusions in soils, and also the confinement of the soil beneath footing is somewhat increased due to the presence of reinforcements.

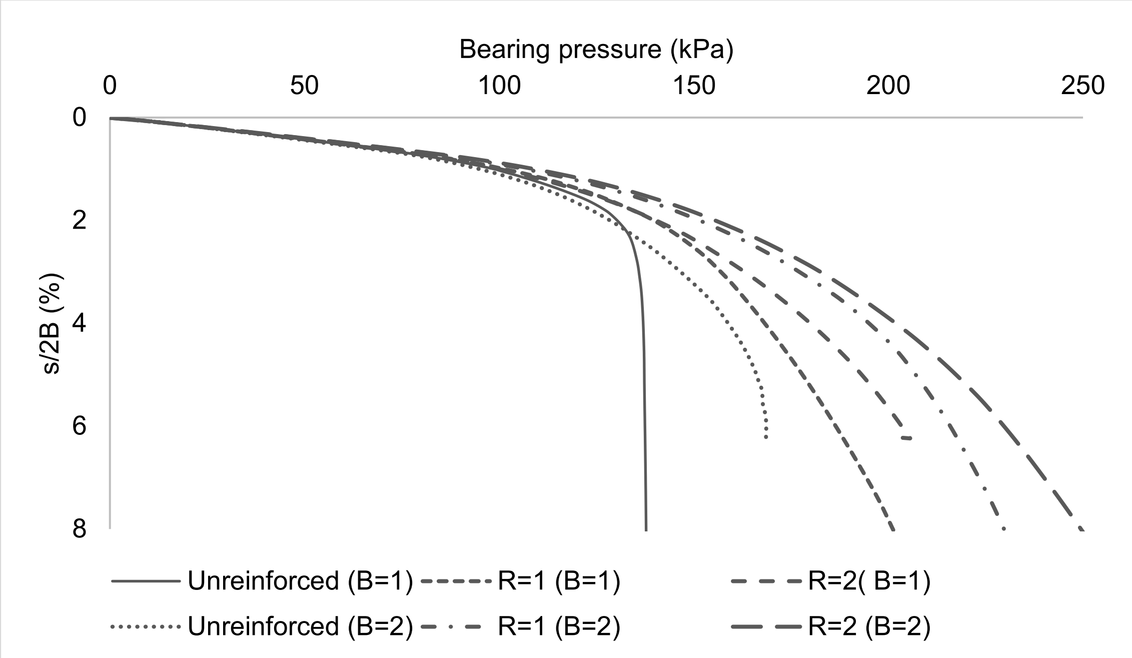


Figure 4.48. Bearing pressure-normalised settlement curves for single strip footing on GB and RGB overlying weak soil (H/B=1, R is number of layers of reinforcement)

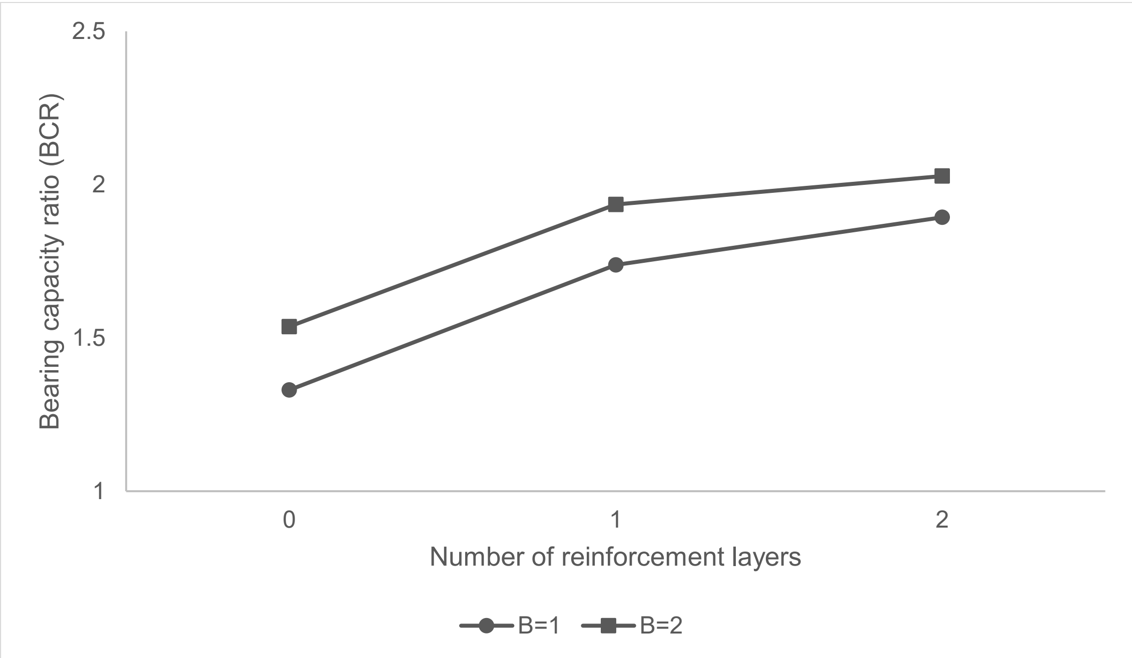


Figure 4.49. BCR vs number of reinforcement layers for footing widths of 1m and 2 m for single strip footing on GB/RGB overlying weak soil (H/B=1) without void

4.3.4.2 Two Adjacent Strip Footings on Reinforced Granular Bed Overlying Clay without Voids

The interference effect of two adjacent strip footings, placed on RGB overlying weak soil is being studied by analysing the interference factor with reinforcement (IFr). The interference factor with reinforcement (IFr) is defined as shown in Equation 4.13.

$$\text{IFr} = \frac{\text{Load carrying capacity of the footing in question in the presence of an adjacent footing on RGB overlying weak soil with no void}}{\text{Load carrying capacity of a single independent strip footing on RGB overlying weak soil with no void}} \quad (4.13)$$

Length of reinforcement is provided in two ways as continuous reinforcement and discontinuous reinforcement. The variation of interference factor with reinforcement (IFr) with spacing ratio, (S/B) for footing width 1m is shown in figure 4.50. The number of layers is seen to increase IFr values. Continuous reinforcement is seen to perform better by giving higher IFr values. The number of layers is also seen to increase IFr values. Ghazavi and Lavasan (2008) numerically examined the interference effect on closely spaced footings with reinforcement and reported that interference factors are larger with geogrid than unreinforced case. Kumar and Saran (2003) conducted model tests on closely spaced strip footings on reinforced soil. Continuous reinforcements are found to effective in reducing the tilt compared to discontinuous reinforcement. The bearing capacity of closely spaced footings increases with the provision of footing size reinforcement layers in the foundation soil beneath the footing, and the effect is similar to that of a rigid deep footing placed at a depth of the lowermost layer of reinforcement.

The combined influence of reinforcement and granular bed on the interference of two adjacent strip footings with underlying clay is being studied by analysing the interference factor due to the combined effect (IFc). IFc is defined, as shown in Equation 4.14. The interference factor due to the combined effect of footing width 1m is shown in figure 4.51. Continuous reinforcement is seen to perform better by giving higher IFc values. The number of layers also seen to increase IFc values.

$$\text{IFc} = \frac{\text{Load carrying capacity of the footing in question in the presence of an adjacent footing on RGB overlying weak soil with no void}}{\text{Load carrying capacity of a single independent strip footing on GB overlying weak soil with no void}} \quad (4.14)$$

IFc values in figure 4.51 are significantly higher than IF'_1 value in figure 4.36. This confirms the contribution of reinforcements in a granular bed. The reinforcement effect is seen to be particularly effective in the case of continuous reinforcement up to spacing of S/B=1.5. Due to the increasing interference effect, the vertical stresses on the granular soil in the space between the footings increases, which in turn causes larger strains (tensile forces) in the continuous reinforcements.

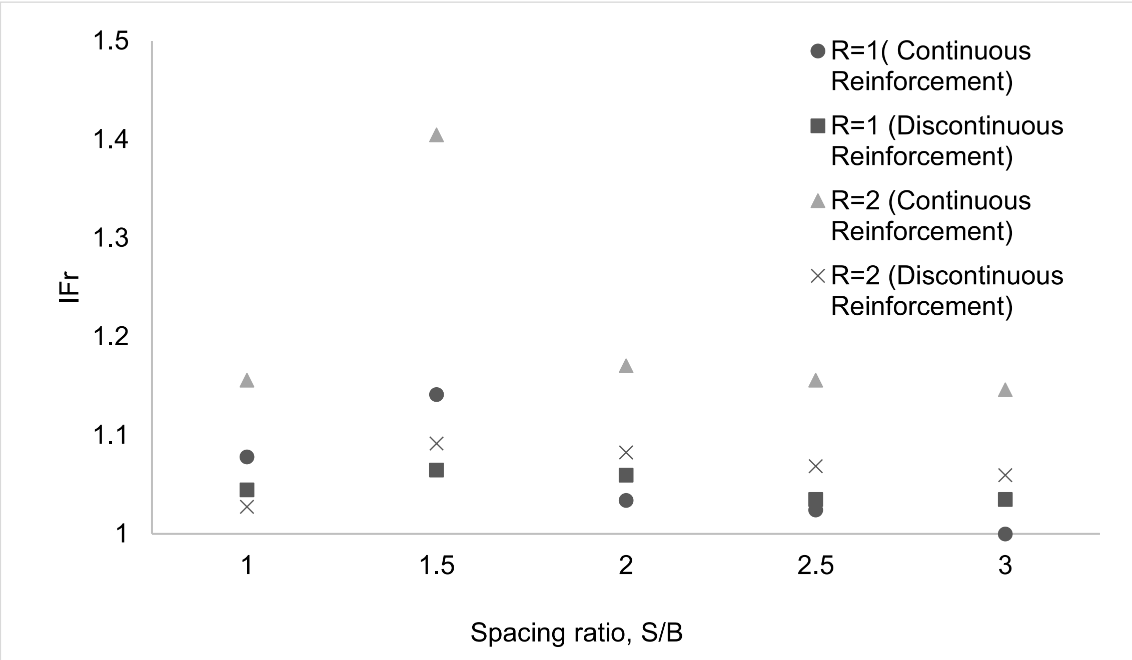


Figure 4.50. Variation of IFr with spacing ratio, S/B, for footing width of 1 m on RGB overlying weak soil (H/B=1, R is number of layers reinforcement)

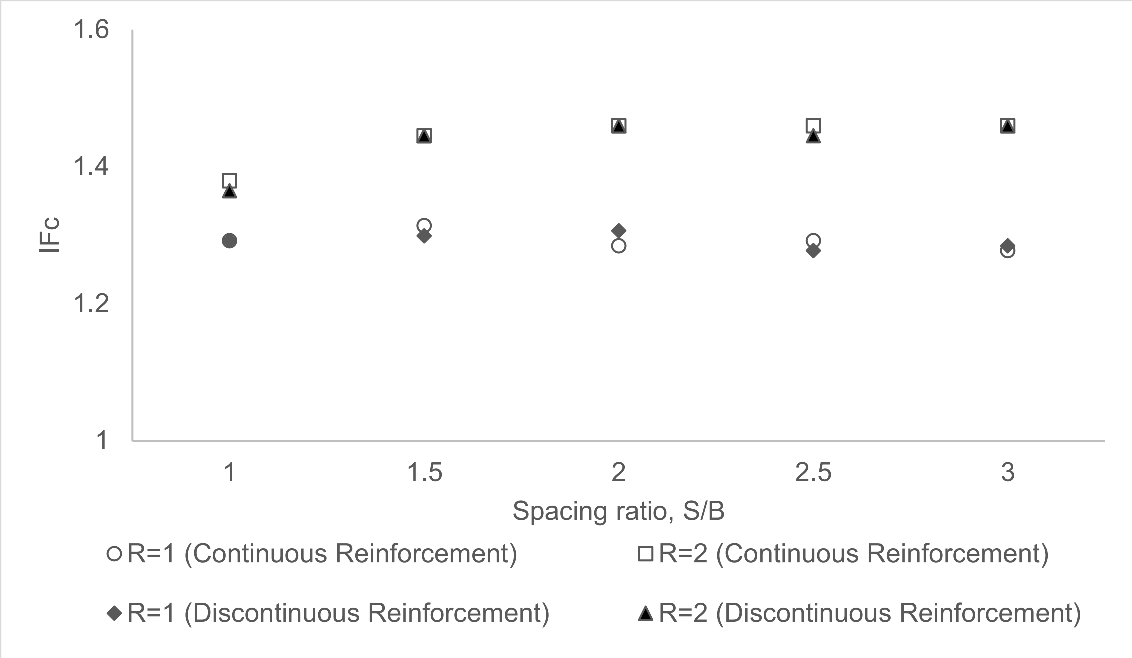
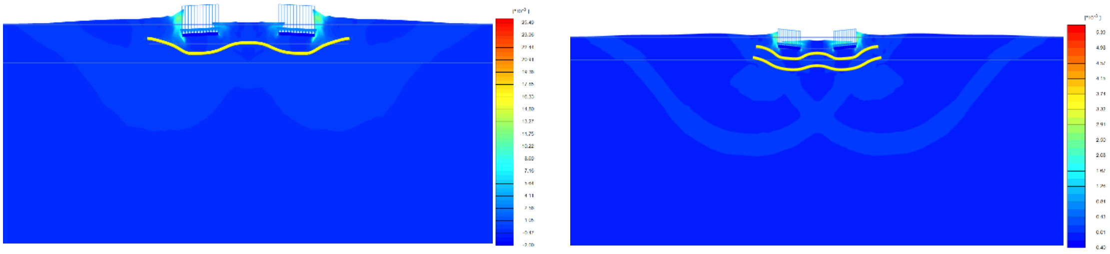


Figure 4.51. Variation of IFc with spacing ratio, S/B, for footing width of 1m on RGB overlying weak soil (H/B=1, R is number of layers reinforcement)

4.3.4.3. Study of the Failure Surfaces

The incremental shear strain contour pattern beneath the strip footings on RGB overlying weak soil without void/s are shown in figure 4.52. The presence of reinforcement in RGB over weak soil (as compared to GB over weak soil with no reinforcements) will alter the mechanism of force transfer. Reinforcements get pulled inwards considerably due to the downward forces exerted by two footings if the pull forces are large. Also, there will be the lateral movement of granular material, below and on either side of individual footings if the GB is sparsely reinforced. Lateral movement of granular soil could be restrained if GB is densely reinforced. The reinforcement between the footings being continuous cannot be pulled to the same extent, as its free end, unless it breaks or ruptures (Kumar and Saran 2003). Therefore, the stiffness of the granular bed along the width of the footing varies. This, in turn, causes the footings to tilt (Figure 4.52).



(a) S/B=1.5, R=1 (b) S/B=1.5, R=2

Figure 4.52. Incremental shear strain contour in the case of two adjacent strip footings with S/B=1.5 on RGB overlying weak soil for 1m wide footings (H/B=1) (a-b)

4.3.4.4. Single Strip Footing on RGB Overlying Clay with A Void Below the Centre of Footing

Single void of 0.5B diameter is considered under single strip footing resting on RGB overlying weak soil (Figure 3.18 a-b). In this case reduction factor, RF-RGB is defined as in Equation 4.15.

$$\mathrm{RF-RGB} = \frac{\begin{array}{c}\text{Load carrying capacity of a strip footing}\\ \text{on RGB overlying weak soil with a void}\end{array}}{\begin{array}{c}\text{Load carrying capacity of a strip footing on RGB}\\ \text{overlying weak soil without a void}\end{array}} \qquad (4.15)$$

Figure 4.53 shows the variation of reduction factor (RF-RGB) with depth ratio, Y/B when the void is considered to be located right below the centre line of footing in the weak soil (X/B=0). Figure 4.54 indicates the variation of improved reduction factor, IRF-RGB, with depth ratio Y/B, for X/B=0, for single void below strip footing on RGB overlying weak soil (B=1m, H/B=1, R=0,1, 2). IRF-RGB is defined as in Equation 4.16.

$$\mathrm{IRF-RGB} = \frac{\begin{array}{c}\text{Load carrying capacity of a strip footing}\\ \text{on RGB overlying weak soil with a void}\end{array}}{\begin{array}{c}\text{Load carrying capacity of a strip footing on GB}\\ \text{overlying weak soil without a void}\end{array}} \qquad (4.16)$$

This IRF-RGB quantifies the reduction in load-bearing capacity due to the presence of a void and improvement in load-bearing capacity due to the reinforcement effect. Figures 4.53 and 4.54 clearly show that there is an advantage of providing reinforcement in the granular bed over void/s. From figure 4.54, it is amply clear that without any reinforcement, the presence of void decreases the bearing capacity values to below that of granular bed on clay without void. However, with reinforcements up to two layers, the bearing capacities of RGB over clay with a void, is greater than a GB on clay without void. The reinforcement soil system with sufficient geogrid-reinforcement and sufficient void embedment depth behaves much more stiffly and thus capable of handling greater loads with a lower settlement and those in unreinforced soil without a void (Asakereh et al. 2013). This proves the efficiency of RGB on clay with the void.

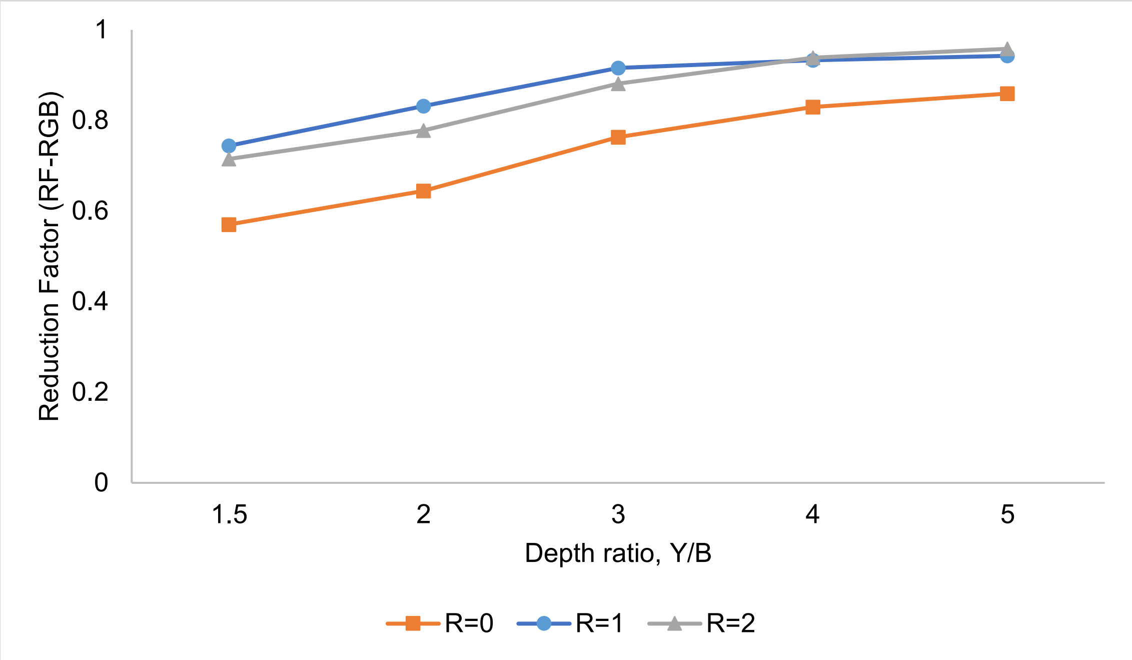


Figure 4.53. Variation of reduction factor, RF-RGB with depth ratio (Y/B), for X/B=0, for single void below single strip footing on RGB overlying weak soil for footing width 1m (H/B=1, R=0, 1, 2; R is number of layers of reinforcement)

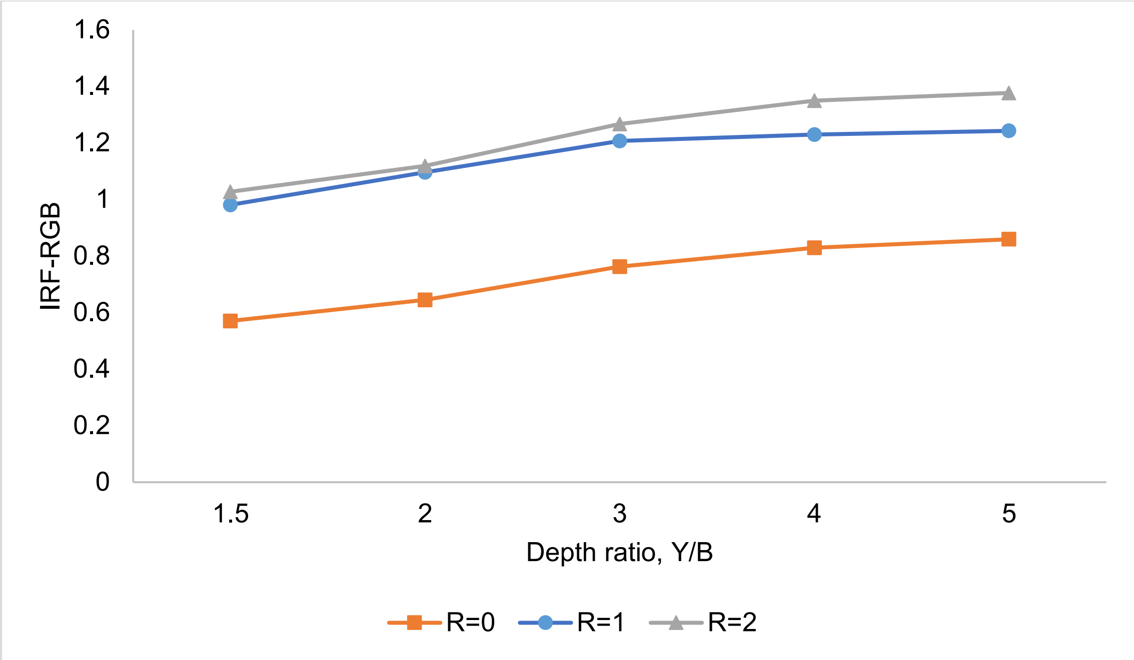


Figure 4.54. Variation of improved reduction factor, IRF-RGB, with depth ratio (Y/B), for X/B=0, for single void below single strip footing on RGB overlying weak soil for footing width 1m (H/B=1, R=0, 1, 2; R is number of layers of reinforcement)

4.3.4.5. Two Adjacent Strip Footings on GB Overlying Weak Soil with Void Below the Centre of Each Footing

Two adjacently placed strip footings are considered on the surface of GB overlying weak soil with a void below the centre of each footing (Figure 3.18c). The void is considered to be circular of diameter 0.5 times the width of the footing. Depth ratio, Y/B for the two voids is taken as 1.5 with X/B=0. To study the interference effect of two closely placed strip footings on GB overlying weak soil with the void, on the bearing capacity of soil; interference factor of bearing capacity with void (IF'_{v1}) is determined in each case. The interference factor of bearing capacity with void (IF'_{v1}) is defined as follows in Equation 4.17.

$$IF'_{v1} = \frac{\text{Load carrying capacity of the footing in question in the presence of an adjacent footing on GB overlying weak soil with void}}{\text{Load carrying capacity of single independent strip footing on GB overlying weak soil with void}} \quad (4.17)$$

Figures 4.55 and 4.56 show the variation of IF'_{v1} with different spacing ratios (S/B values) between the footings varying from 1.0 to 3.0 for different H/B ratios. The interference factor for both the footing widths increases initially with the increase in spacing up to a maximum value, then decreases with the further increase in spacing. In the case of B=1m (H/B=1.5), 1.5B is obtained as optimum spacing. In the case of B=2m (H/B=1.5), 2B is obtained as optimum spacing. Interference factor value with void IF'_{v1} is observed to increase with the increase in footing width. This is due to the increased confinement of granular soil beneath and between the wider footing.

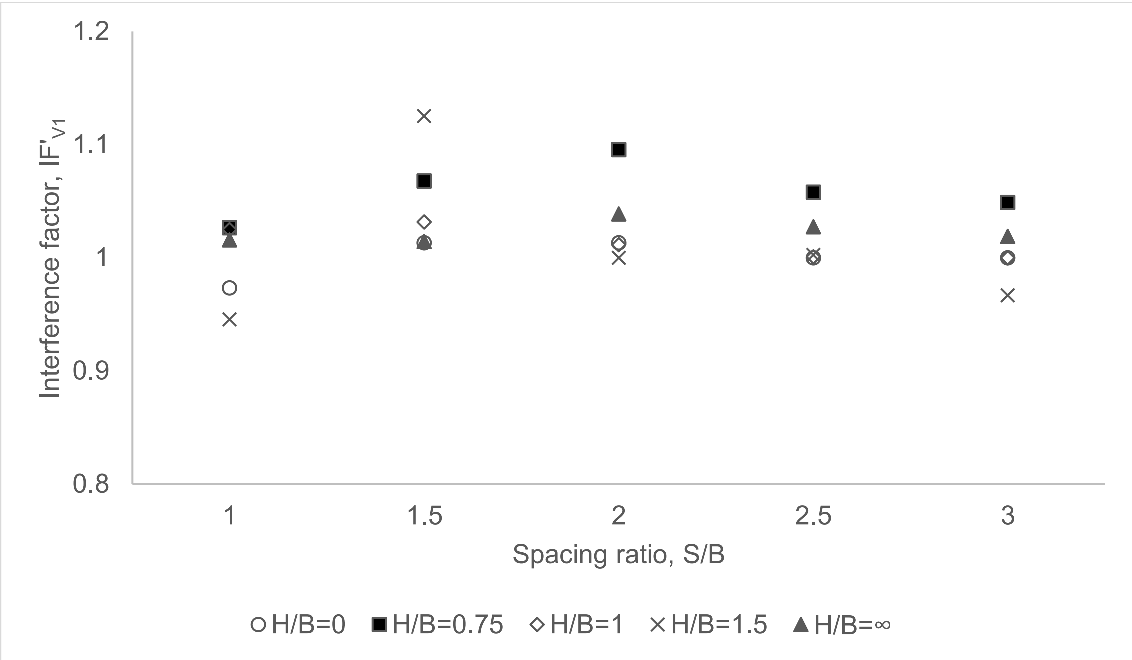


Figure 4.55. Variation of interference factor (IF'_{v1}) with spacing ratio, S/B, for footing width of 1 m, for different thickness of granular bed (H/B) overlying weak soil with voids

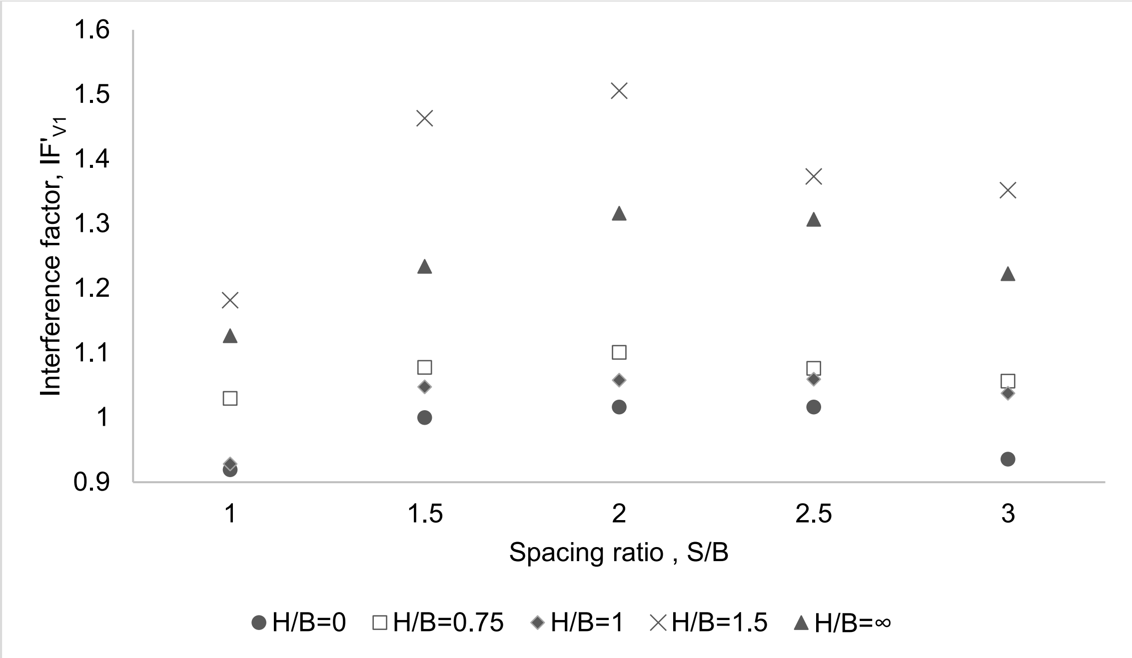


Figure 4.56. Variation of interference factor (IF'_{v1}) with spacing ratio, S/B, for footing width of 2 m, for different thickness of granular bed (H/B) overlying weak soil with voids

4.3.4.6. Two Adjacent Strip Footings on RGB Overlying Weak Soil with Voids Below the Centre of each Footing

The interference effect of two adjacent strip footings, resting on RGB overlying weak soil with voids (Figures 3.18 d-g) are being studied by analysing the interference factor with reinforcement and void (IFrv). Interference factor with reinforcement and void (IFrv) is defined as shown in Equation 4.18.

$$\text{IFrv} = \frac{\text{Load carrying capacity of the footing in question in the presence of an adjacent footing on RGB overlying weak soil with void}}{\text{Load carrying capacity of a single independent strip footing on RGB overlying weak soil with void}} \qquad (4.18)$$

The variation of interference factor with reinforcement and void (IFrv) with spacing ratio, (S/B) for footing width B=1m is shown in figure 4.57. IFrv values are seen to be fairly constant for different spacings, i.e. S/B values. However, the number of reinforcement layers is seen to decrease IFrv values.

The combined influence of reinforcement and granular bed on the interference of two adjacent strip footings overlying weak soil with voids is being studied by analysing the interference factor due to the combined effect (IFcv) (Figure 4.58). IFcv is defined, as shown in Equation 4.19. Continuous reinforcement with more number of reinforcement layers, i.e. (R=2) is seen to perform better by giving higher IFcv values. Again, IFcv values are seen to be fairly constant for different S/B values.

$$\mathrm{IFcv} = \frac{\text{Load carrying capacity of the footing in question in the presence of an adjacent footing on RGB overlying weak soil with void}}{\text{Load carrying capacity of a single independent strip footing on GB overlying weak soil with void}} \quad (4.19)$$

IF'_{v1}, as defined in Equation 4.17 and IFcv, as defined in Equation 4.19, are similar except IF'_{v1} deals with a granular bed and IFcv deals with RGB. In IF'_{v1} (Figures 4.55-4.56), only the interference effect is highlighted whereas the case of IFcv (Figures 4.58-4.59), highlights the combined effect of interference and reinforcement. It can be seen the IFcv values are significantly higher than IF'_{v1} values which indicate the aspect of improvement (improvement in load carrying capacity) that reinforcement adds to the composite ground, i.e., RGB on clay.

Figure 4.57. Variation of IFrv with spacing ratio, S/B for footing width of 1 m on RGB overlying weak soil with voids (H/B=1, R is number of layers of reinforcement)

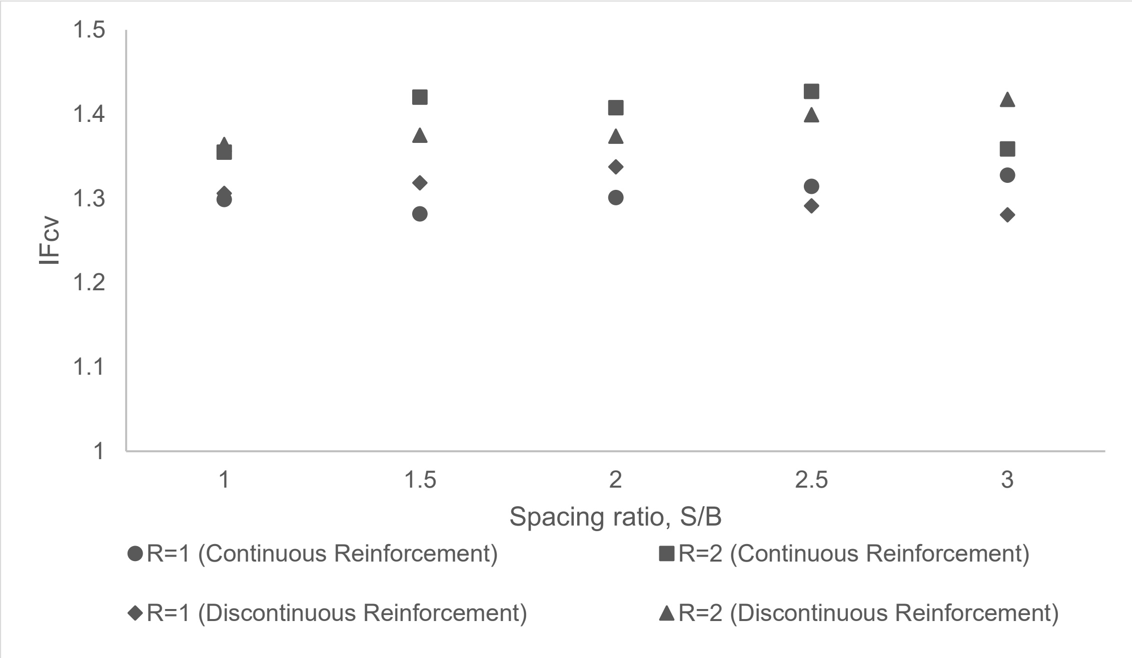


Figure 4.58. Variation of IFcv with spacing ratio, S/B for footing width of 1m on RGB overlying weak soil with voids (H/B=1, R is number of layers reinforcement)

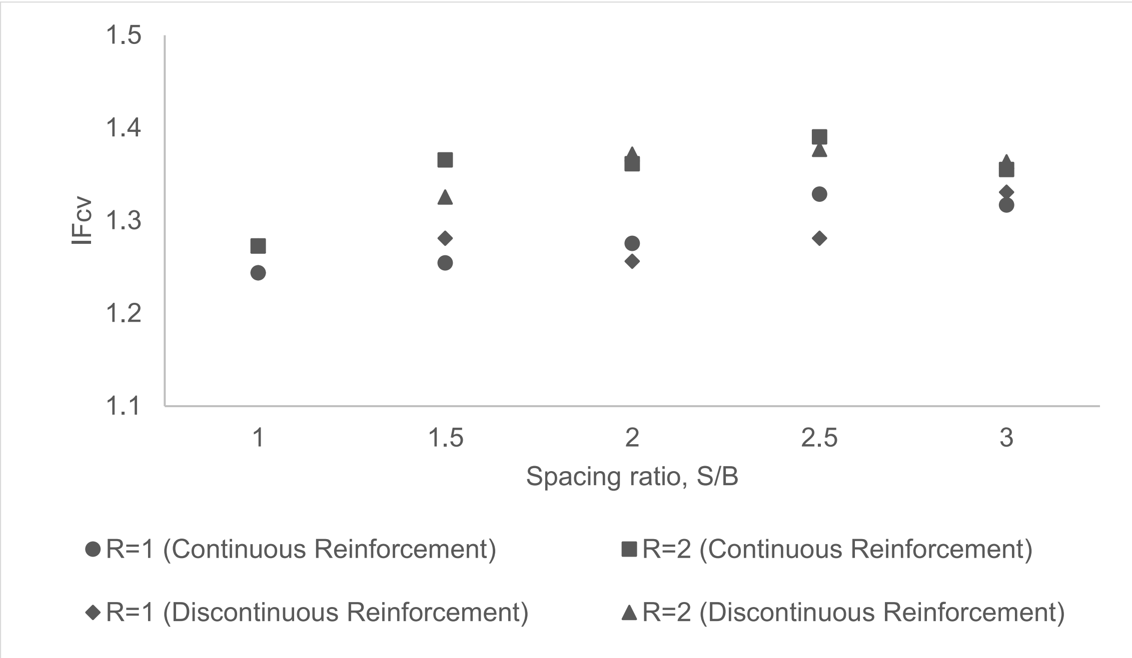
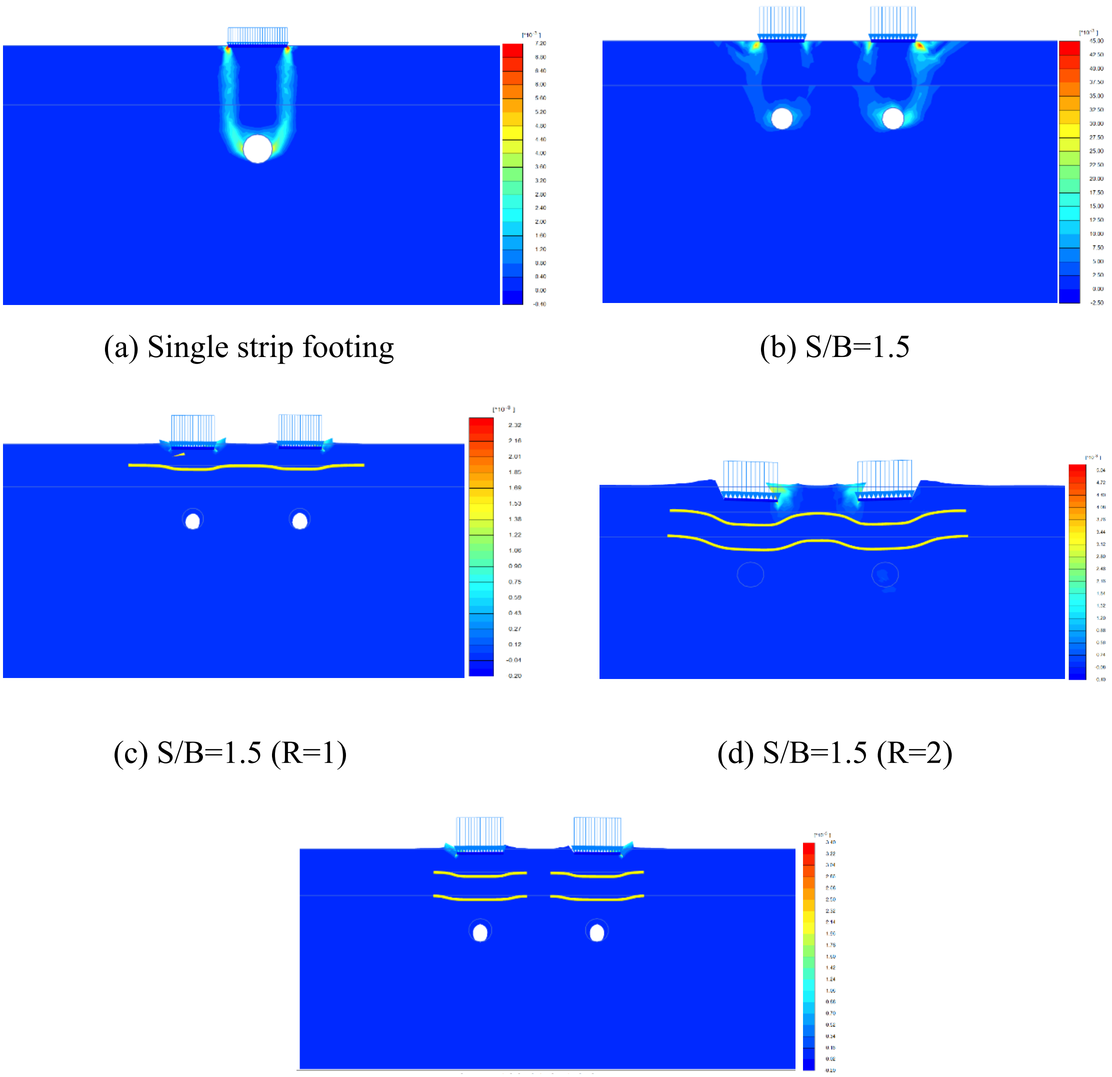


Figure 4.59. Variation of IFcv with spacing ratio, S/B for footing width of 2 m on RGB overlying weak soil with voids (H/B=1, R is number of layers reinforcement)

4.3.4.7. Study of the Failure Surfaces

The incremental shear strain contour pattern beneath the strip footings on GB/RGB overlying weak soil with void/s are shown in figure 4.60. When the void is formed in soft clay nearest to footings, the failure surface developed tends to move towards the void and is found to be narrower and smaller than the no void case. Locating the void exactly beneath footing causes a punching failure in the soil (Kiyosumi et al. 2007).



(a) Single strip footing

(b) S/B=1.5

(c) S/B=1.5 (R=1)

(d) S/B=1.5 (R=2)

(e) S/B=1.5 (R=2, Discontinuous reinforcements)

Figure 4.60. Incremental shear strain contour in the case of single and two adjacent strip footings with S/B=1.5 on GB/RGB overlying weak soil with void/s at Y/B=1.5 for 1m wide footings (H/B=1, R -Number of layers of reinforcement) (a-e)

CHAPTER 5

ANALYTICAL MODELLING

5.1. GENERAL

Most of the previous studies in the literature which studied interference effects of adjacent strip footings on granular bed overlying weak soil have not provided an analytical model. This research work attempted to provide an analytical model to estimate the ultimate bearing capacity of two and three adjacent strip footings resting on granular bed overlying weak soil, with a fair and acceptable degree of accuracy. The accuracy of the proposed model has verified with finite element simulations and the percentage error is about 13%.

In several situations, a granular bed (GB) is laid over weak soil as a simple ground improvement method and for other practical reasons. In this study, granular bed overlying soft clay is being considered. The parameters varied are the clear spacing between the adjacent strip footings, width of footings, thickness of the top granular bed, and number of footings.

From the insights gained from finite element simulations, a simple analytical model has been proposed to estimate the ultimate load-carrying capacity and interference factor of adjacent strip footings resting on granular bed overlying weak soil. From finite element simulations, it is seen that punching shear failure of footing/s is the dominant failure mechanism for two or three adjacent footings on the granular bed over clay. The earlier model proposed by Shivashankar et al. (1993) for an isolated footing resting on a reinforced granular bed overlying clay has been extended for adjacent and interfering footings. A punching shear failure mechanism, similar to Shivashankar et al. (1993) is envisaged in the present analytical model as well. It is assumed that rigid surface footings are resting on granular fill overlying weak soil. The surcharge effect is neglected due to the interference phenomenon in the upper granular layer. The adjacent strip footings are assumed to be simultaneously loaded. The methodology adopted in this study is shown in the flowchart (Figure 5.1).

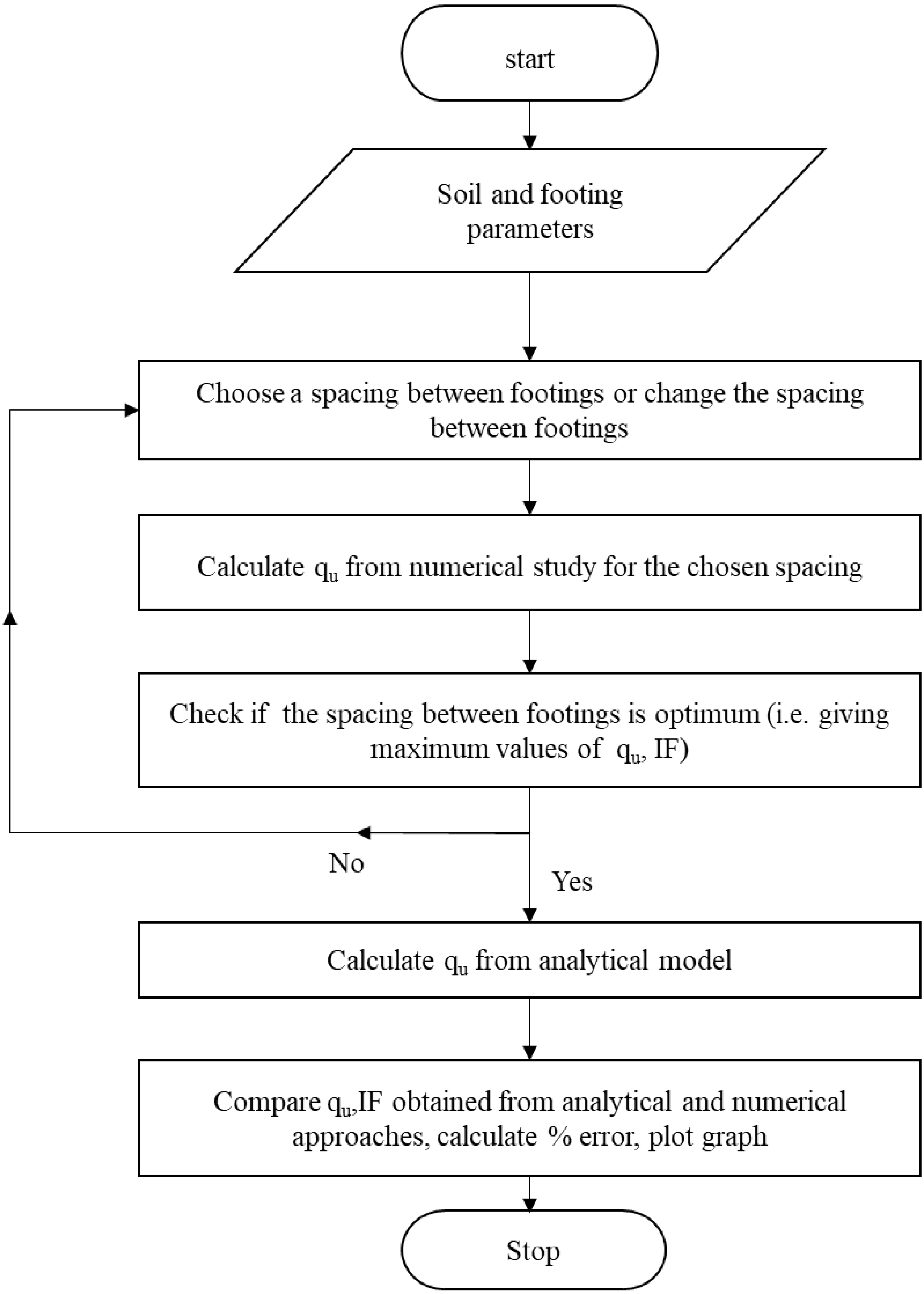


Figure 5.1. Methodology flowchart

5.2. ANALYTICAL MODEL FOR A SINGLE STRIP FOOTING ON GRANULAR BED OVERLYING CLAY WITHOUT VOID

In this study, the analytical model considered is based on the model developed and used by earlier researchers (Shivashankar et al. 1993, Rethaliya and Verma, 2009) based on the punching shear failure mechanism, which hereinafter will be referred to as 'punching shear analytical model'. It is envisaged that both the footing and the portion of the granular bed (GB) immediately below the footing work in unison to punch through the soft soil underneath. The load-carrying capacity of the footing is taken as the sum of total shearing resistances along the two vertical planes through the edges of the strip footing in the upper granular layer and the load-carrying capacity of the soft clay beneath the GB (Figure 5.2).

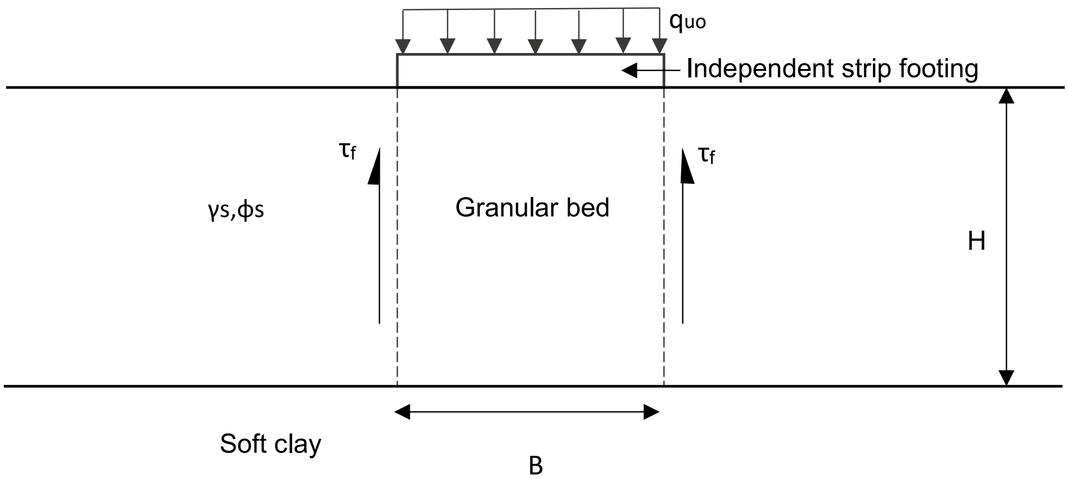


Figure 5.2. 'Punching shear analytical model' for a single strip footing on granular bed overlying clay

Therefore, the improvement in bearing capacity of a strip footing on a granular bed (GB) overlying clay is attributed solely to the shear layer effect in the upper granular layer. The shear layer effect considered is similar to the one considered by Shivashankar et al. (1993) (while studying the bearing capacity of footings on the reinforced granular bed (RGB) overlying soft clay). It can be mathematically represented, as shown below in Equation 5.1.

$$q_{uo} = c_u Nc + \Delta q_{SL} \qquad (5.1)$$

Where $q_{uc} = c_u N_c$ is bearing capacity of clay ground; Δq_{SL} denotes the improvement in bearing capacity due to shear layer effect and q_{uo} represents the bearing capacity of an independent strip footing on the composite/layered ground with no void and no interference.

The improvement in bearing capacity is quantified in terms of the Bearing Capacity Ratio (BCR). BCR is defined as the ratio of the bearing capacity of the improved ground (q_{uo}) to the bearing capacity of the unimproved clay ground (q_{uc}). BCR can be expressed as:

$$\mathrm{BCR} = \frac{q_{uo}}{q_{uc}} = 1 + \Delta \mathrm{BCR}_{SL} \quad (5.2)$$

Where ΔBCR_{SL} -Improvement in bearing capacity ratio due to the shear layer effect.

Previous experimental and numerical studies by Das et al. (1993), Anaswara and Shivashankar (2020 a,b) have proved that if the thickness of the upper granular bed is more than a critical thickness, then the entire failure surface beneath the footing will be within the granular layer. If the thickness of the upper granular bed is less than the critical thickness, then only the failure surface will reach up to the lower weaker clay layer, and punching shear failure is likely to occur.

$$Q_{u0} = q_{u0}B = cN_cB + (2\tau_f)H \leq q_sB \quad (5.3)$$

Where q_s-Bearing capacity of footing on the sand layer

In the shear layer effect (Shivashankar et al. 1993), the shearing resistances mobilised along the vertical planes at the two edges of the strip footing due to the passive pressure developed in granular soil are considered. The equations given for strip footings are

$$\tau_f = \frac{k_p \gamma_s H^2}{2} \tan\phi_s \quad (5.4)$$

$$\Delta q_{SL} = \frac{2\tau_f}{B} \quad (5.5)$$

$$\Delta \mathrm{BCR}_{SL} = \frac{2\tau_f}{B N_C C_u} \quad (5.6)$$

Where $N_C C_u$- Bearing capacity of underlying weak soil (q_{uc}), τ_f - Punching shear resistance along a vertical plane due to shear layer effect, kp - Coefficient of passive earth pressure, Φs - Angle of internal friction of the granular material

5.2.1.Validation of the 'Punching Shear Analytical Model' For Single Independent Strip Footing

In the present study, the parameters considered are as follows:

γ_{sand}=18.2 k N/m^3, ϕ_s= 30^0, $k_P = \frac{1+\sin\phi_s}{1-\sin\phi s}$ =3, B=1m, H=1m , c=20 k N/m^2 , Nc=5.14

$$\tau_f = \frac{3\ X18.2X1X1X0.5773}{2} = 15.76 \text{ kN/m} \qquad (5.7)$$

$$q_{uc}=20x5.14=102.8 \text{ kN/m}^2 \qquad (5.8)$$

Substituting 5.7 and 5.8 in 5.3,

$$Q_{u0}/B = q_{u0} = 102.8 + (2x15.76) = 134.32 \text{ kN/m}^2 \qquad (5.9)$$

The corresponding bearing capacity of a single strip footing on GB overlying clay obtained from finite element analysis is 137 kN/m^2.

To verify the veracity of the analytical method, one of the most relevant case studies have been numerically simulated and the results obtained are compared. Das et al. (1993) conducted some experiments to study the load-carrying capacity of a strip footing on dense sand overlying soft clay. The experiments were conducted in a box measuring 1.22 m length x 0.305 m width x 0.915 m height. A top layer of dense sand with a unit weight of 17.29 kN/m^3 and friction angle of 39.8^0, and lower soft clay with undrained shear strength as 5.51 kN/m^2 were used. The width of the model strip footing used was 101.6mm. The thickness of dense sand was varied.

Figure 5.3 shows the comparison of the ultimate bearing capacities of single strip footings on the granular bed, of varying thicknesses, i.e. (H/B) values (H/B varying from 1 to 5), overlying weak soil obtained by experimental studies of Das et al. (1993) with the 'punching shear analytical model' and results of numerical studies from this research study. The bearing capacities obtained by the 'punching shear analytical model' are in good agreement with the results of numerical analysis of the present study and the experimental results of Das et al. (1993).

Figure 5.3. Comparison of results of the 'punching shear analytical model' for single independent strip footing (for varying H/B values) with the experimental results of Das et al. (1993) and numerical analysis results from the present study

5.2.1.1. Comparison Between Results of 'Punching Shear Analytical Model' and Finite Element Analysis

The values of bearing capacities of single strip footings predicted by the 'punching shear analytical model' on GB overlying clay are compared with the results obtained from finite element analyses and some experimental results available in the literature. Table 5.1 shows the predicted and numerical ultimate bearing capacity values for single strip footing on granular bed overlying weak soil. Figure 5.4 shows a comparison between predicted values of the ultimate bearing capacities with the results of experimental and numerical studies. Figure 5.5 shows a comparison between predicted values with experimental and numerical studies of bearing capacity ratios (BCR). It can be observed that the 'punching shear analytical model' predicts the values of bearing capacities and bearing capacity ratios reasonable well.

Table 5.1. Predicted and numerical ultimate bearing capacity values for single strip footing on granular bed overlying weak soil

B (m)	H (m)	q_c (kPa) (1)	τ_f	Δq_{SL} (2)	Punching shear analytical model q_{u0} (kPa) (1)+(2)	Numerical analysis q_u (kPa)	Percentage error
1	0.75	102.8	8.87	17.73	120.53	118	2.14
1	1	102.8	15.76	31.52	134.32	137	-1.96
1	1.5	102.8	35.46	70.92	173.72	157	10.65
2	1.5	102.8	35.46	35.46	138.26	145	-4.65
2	2	102.8	63.04	63.04	165.84	169	-1.87
2	3	102.8	141.84	141.84	244.64	218	12.22

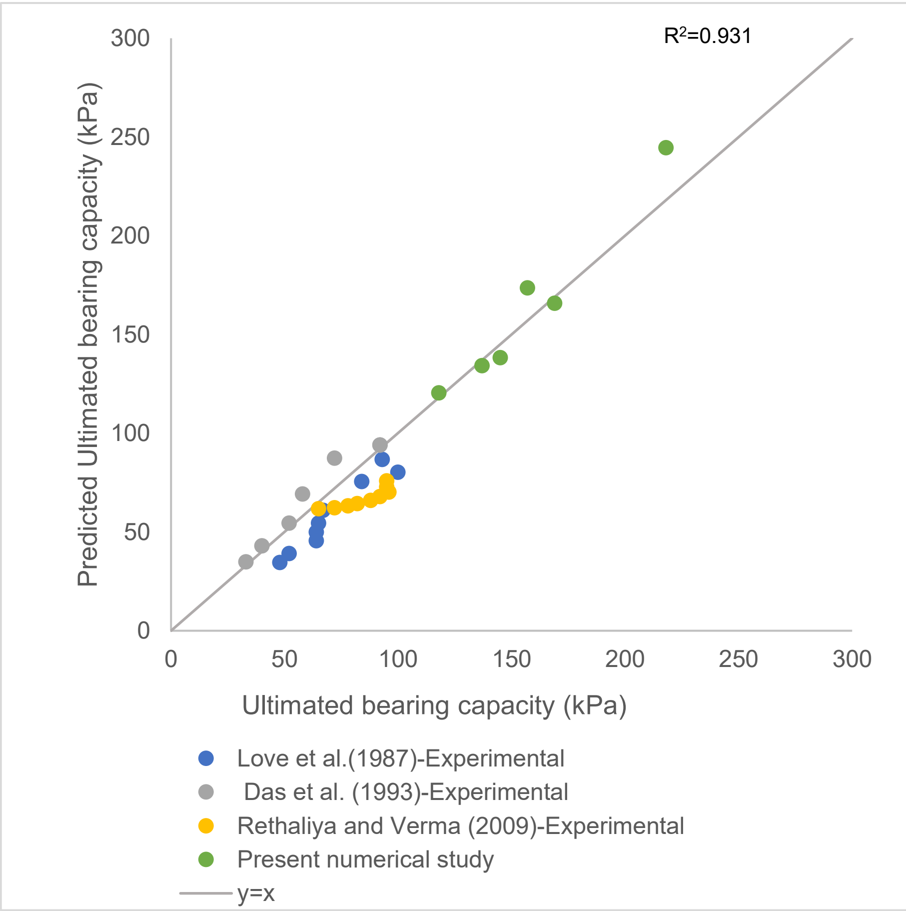


Figure 5.4. Comparison between predicted values of ultimate bearing capacity from 'punching shear analytical model' for single strip footing with results of experimental and numerical studies

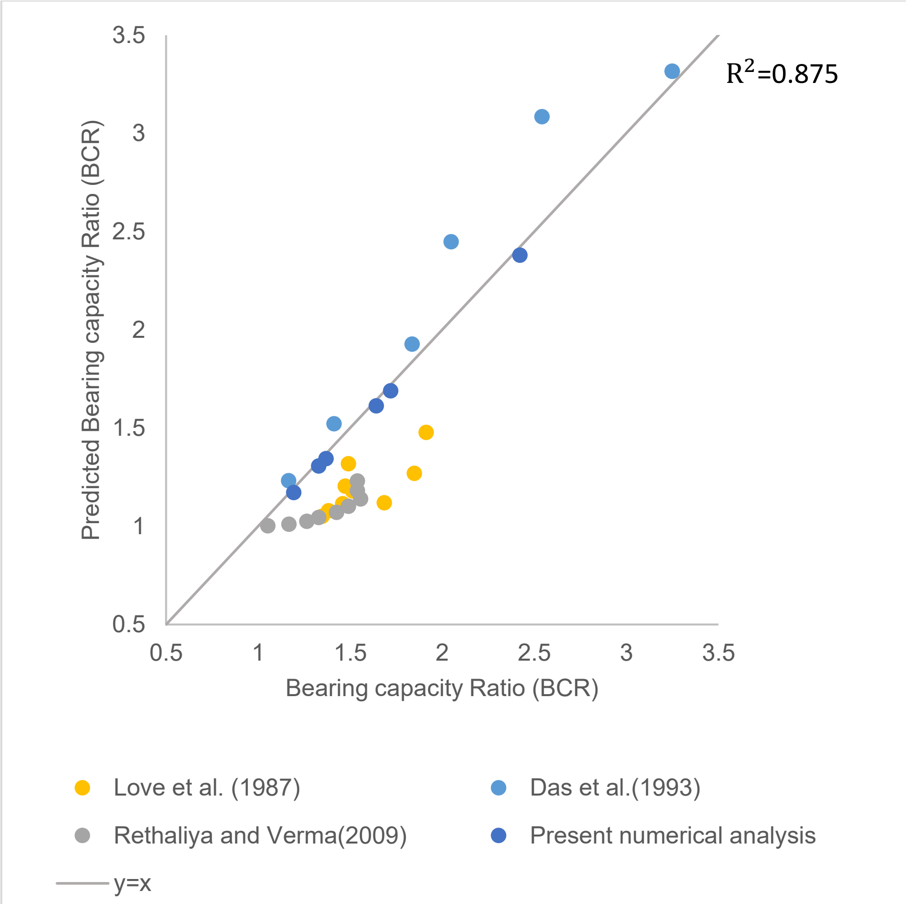


Figure 5.5. Comparison between predicted values of bearing capacity ratio (BCR) from 'punching shear analytical model' for single strip footing with results of experimental and numerical studies

5.3.ANALYTICAL MODEL TO PREDICT THE LOAD-CARRYING CAPACITY OF THE INTERFERED FOOTING AND INTERFERENCE FACTOR, IN CASE OF TWO ADJACENT STRIP FOOTINGS ON GRANULAR BED (GB) OVERLYING CLAY [WITH NO VOID AND SIMULTANEOUSLY LOADED]

When two footings are placed adjacent to each other on GB, or GB overlying clay, there will be an 'interference effect'. In the case of two adjacent strip footings on GB overlying clay and simultaneously loaded (Figure 5.6), an analytical model is proposed to predict the ultimate bearing capacity of the interfered footing and the interference factor. The proposed model is again based on the philosophy of the punching shear mechanism. It is an extension/modification of the punching shear model for a single strip footing on granular bed overlying clay, as explained earlier in section 5.2. This proposed model will be hereinafter be referred to as 'proposed analytical model for interfered footing'. The proposed model is applicable at the optimum spacing between the adjacent footings (i.e., S/B=1.5, Figure 4.36). The granular bed thickness H/B is to be equal to or less than optimum thickness for punching action of the footing along with sand block into the clay layer to occur.

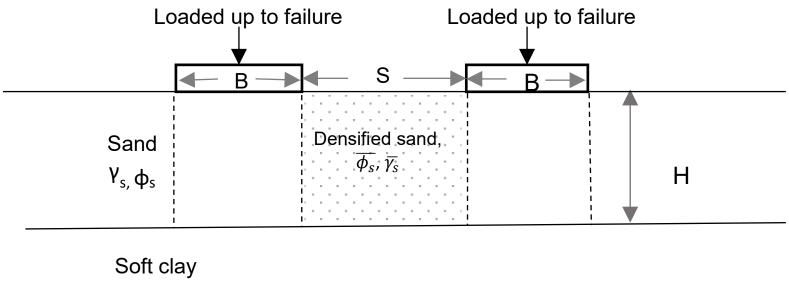


Figure 5.6. Adjacent strip footings on granular bed overlying weak soil

Both the footings are interfered footings in the case of two adjacent surface strip footings. Similar Equations as 5.4 and 5.5 are adopted for the shear layer effect, but the passive lateral pressure coefficients (k_p) are not taken the same on the two vertical shearing surfaces on either sides of the strip footing. The lateral passive pressure and the shearing resistance in the interfered zone, i.e. the zone of granular material between the two footings, will be more due to the lateral compression of the granular soil due to the lateral confinement stresses developed due to the vertical loads on the two footings. Maximum lateral compression of the granular soil due to interference effect is seen (from numerical studies) to occur when the footings are optimally spaced (maximum interference factor from numerical analysis)(Figure 5.7).

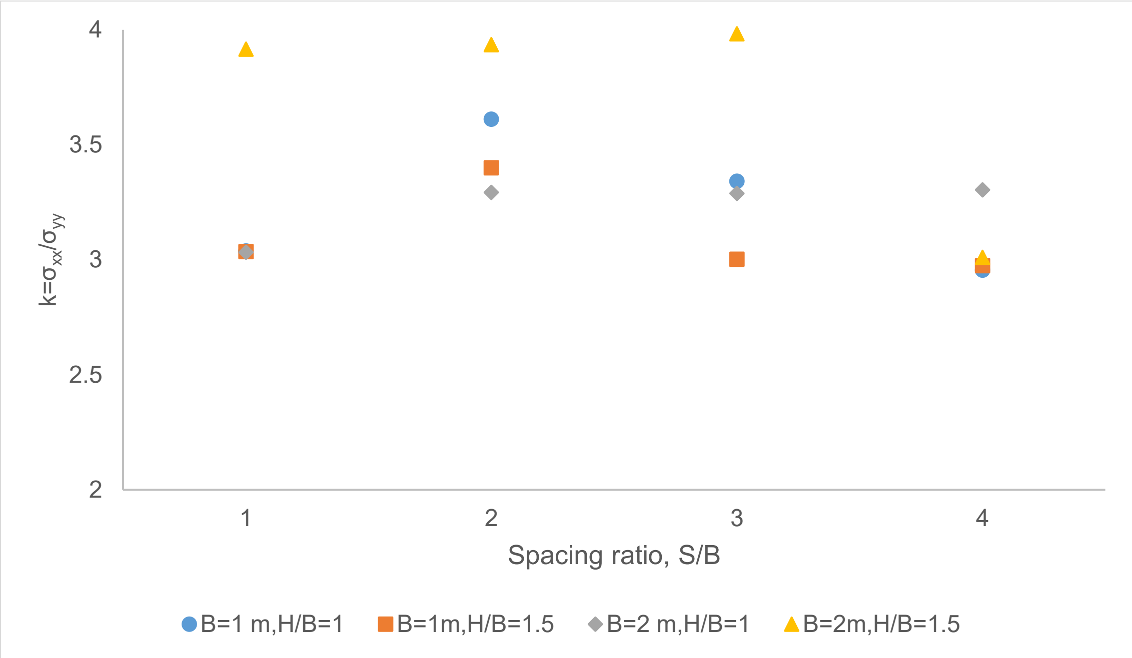


Figure 5.7. Variation of lateral earth pressure coefficient in the interfered zone, with spacing ratio, S/B [from numerical studies]

5.3.1. Interference Factor

To quantify the effect of interference of two adjacently spaced strip footings on the bearing capacity of soil; the interference factor of load carrying capacity (IF'$_1$) is defined as follows in Equation 5.10 below.

$$IF'_1 = \frac{\text{Load carrying capacity of the footing in question in the presence of an adjacent footing on GB overlying weak soil with no void}}{\text{Load carrying capacity of single independent strip footing on GB overlying weak soil with no void}} = \frac{q_{ui}}{q_{uo}} \quad (5.10)$$

The load-carrying capacity of interfered footing (q_{ui}) and that of single independent strip footing (q_{uo}) on GB overlying weak soil with no void (no interference) are calculated by the 'proposed analytical model for interfered footing' and 'punching shear analytical model' respectively. It is observed from experimental and numerical studies that in the case of two strip footings on GB or GB overlying clay, the interference factor increases at first as the spacing between the footings is increased and thereafter, the interference factor of bearing capacity value decreases beyond the optimum spacing (Anaswara and Shivashankar 2020 a,b). The maximum bearing capacity value is noted at the optimum spacing. At the optimum spacing between the adjacent footing, maximum confinement pressure (coefficient of lateral earth pressure 'K') is observed (Figure 5.7).

5.3.2. Validation of the 'Proposed Analytical Model for Interfered Footing'

The densified granular soil mass between the two adjacent footings is assumed to be densified to the maximum with increased density $\overline{\gamma_s}$ and increased friction angle $\overline{\phi_s}$ (Figure 5.6). Maximum value of $\overline{\gamma_s}$ as determined from laboratory experiments is $20\mathrm{kN/m^3}$. Maximum value of $\overline{\phi_s}$ is obtained from the analogy drawn from compaction of sand (and increase of angle of internal friction of sand) below pile tip in case of driven piles (while determining the load-carrying capacity of the pile in bearing in granular material). According to Kishida (1967), the maximum friction angle beneath the pile will be

$$\overline{\phi_s} = \frac{\phi_s + 40}{2} \tag{5.11}$$

Substituting ϕs=30 (angle of internal friction of medium sand considered in the present study) in Equation 5.11, we get $\overline{\phi_s} = \frac{30+40}{2} = 35^0$ as the increased angle of internal friction of sand due to compression in the interference zone.

Results of numerical analysis in the present study also gave a maximum coefficient of lateral earth pressure, k value of soil between footings around 3.7 which corresponds to about $\overline{\phi_s} = 35^0$ (Figure 5.7). With the modified density and friction angle, mobilised shear resistance developed at the densified soil side are estimated as τ'_f (Figure 5.8).

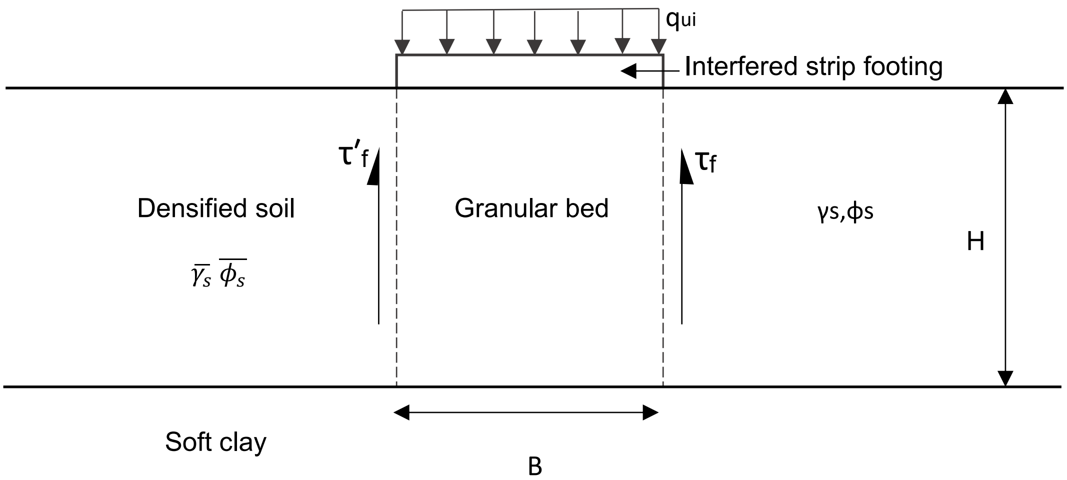


Figure 5.8. Proposed analytical model for interfered footing for adjacent strip footings on granular bed overlying weak soil

$$Q_{ui} = q_{ui}B = q_{uc}B + (\tau_f' + \tau_f)H \leq q_s B \tag{5.12}$$

$$\tau_f' = \frac{\overline{k_p}\,\overline{\gamma_s}\,H^2}{2} \tan \overline{\phi_s} \tag{5.13}$$

$$\overline{k_p} = \frac{1+\sin\overline{\phi_s}}{1-\sin\overline{\phi_s}} \tag{5.14}$$

Where, $\overline{\gamma_s} = 20\text{kN/m}^3$, $\overline{\phi_s} = 35^0$, $\overline{k_p} = 3.69$, B=1m, H=1m, $\tau_f = 15.76\text{kN/m}^2$, c=20kN/m^2 , q_{uc}=20x5.14=102.8 kN/m^2

$$\tau_f' = 25.83\text{kN/m} \tag{5.15}$$

Substituting 5.15 in 5.12,

$$Q_{ui}/B = q_{ui} = 20\text{X}5.14 + (25.83 + 15.76) = 144.39 \text{ kN/m}^2 \tag{5.16}$$

Corresponding bearing capacity of interfered strip footing on GB overlying clay obtained from finite element analysis is 147 kN/m^2.

5.3.2.1. Comparison Between Results of 'Proposed Analytical Model for Interfered Footing' and Finite Element Analysis

The values of bearing capacity of interfered strip footing predicted by the 'proposed analytical model for interfered footing' are compared with those obtained from finite element analyses (Table 5.2). Figure 5.9 shows a comparison between the values of bearing capacity predicted by the proposed analytical model and finite element analyses for interfered footing on GB overlying weak soil.

The comparison between the values of interference factor IF'_1 predicted by the proposed modified analytical model, and finite element analyses for strip footing on GB overlying weak soil are presented in Table 5.3 and figure 5.10. The ultimate bearing capacity values estimated by the proposed analytical model for interfered footing are in good agreement with the values obtained from numerical analysis, with a maximum variation of 12%. Even the Interference factor (IF'_1) values from both analytical and numerical approaches show a maximum variation of 12.7%. The average variation in bearing capacity prediction is about 6% and the average variation in the prediction of IF values are 5 to 6%. The coefficients of determination, R^2, are respectively 0.959 for bearing capacity (Figure 5.9) and 0.904 for interference factor (Figure 5.10) which are reasonably good.

Table 5.2. Predicted and numerical ultimate bearing capacity values for interfered strip footing on granular bed overlying weak soil

B (m)	H (m)	q_c (kPa) (1)	τ_{f1}	τ'_{f1}	Δq_{SL} (2)	Proposed analytical model q_{ui} (kPa)(1)+(2)	Numerical analysis q_{ui} (kPa)	Percentage error
1	0.75	102.8	8.87	14.53	23.40	126.20	119	6.05
1	1	102.8	15.76	25.84	41.60	144.40	147	-1.77
1	1.5	102.8	35.46	58.13	93.59	196.39	185	6.16
2	1.5	102.8	35.46	58.13	46.80	149.60	170	-12.00
2	2	102.8	63.04	103.35	83.20	186.00	201	-7.47
2	3	102.8	141.84	232.54	187.19	289.99	296	-2.03

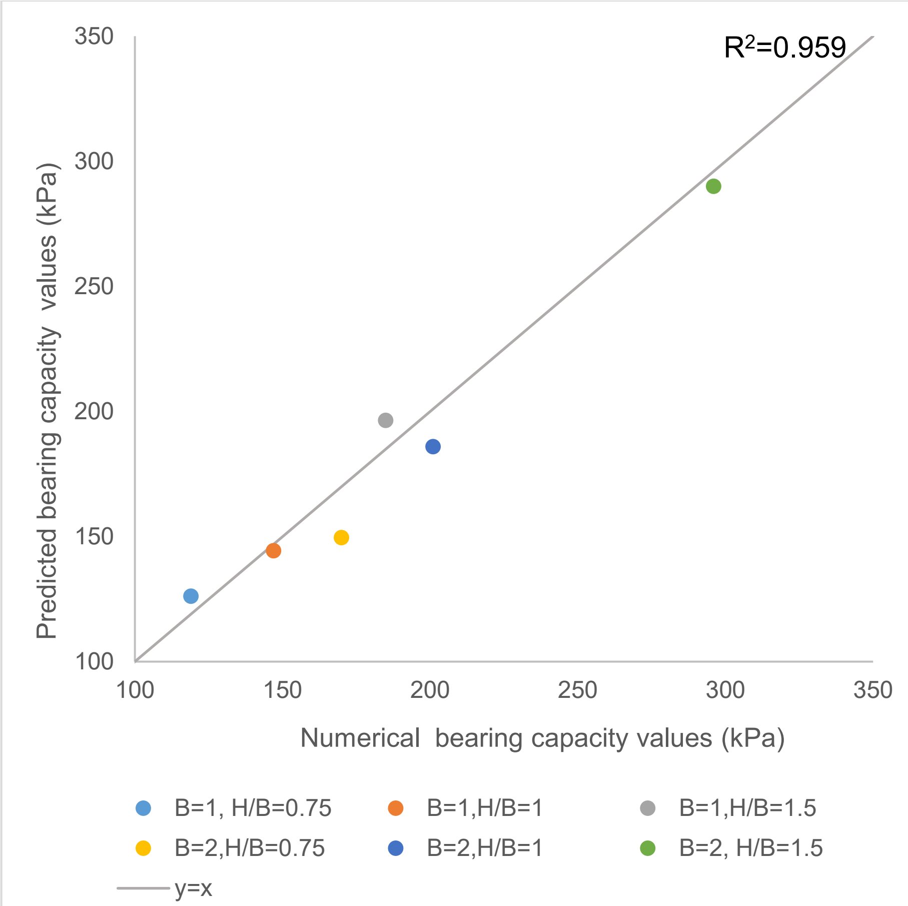


Figure 5.9. Comparison between predicted values of ultimate bearing capacity from 'proposed analytical model' for interfered footing with numerical studies

Table 5.3. Predicted and numerical interference values for interfered strip footing on granular bed overlying weak soil

Specification		Proposed analytical model, q_u (kPa)		Numerical analysis, q_u (kPa)		Interference factor, IF'_1		Percentage error
B (m)	H (m)	Single footing q_{u0}	Interfered Footing, q_{ui}	Single footing, q_{u0}	Interfered Footing, q_{ui}	Proposed model	Numerical analysis	
1	0.75	120.53	126.20	118	119	1.05	1.01	3.82
1	1	134.32	144.40	137	147	1.08	1.07	0.19
1	1.5	173.72	196.39	157	185	1.13	1.18	-4.06
2	1.5	138.26	149.60	145	170	1.08	1.17	-7.71
2	2	165.84	186.00	169	201	1.12	1.19	-5.70
2	3	244.64	289.99	218	296	1.19	1.36	-12.70

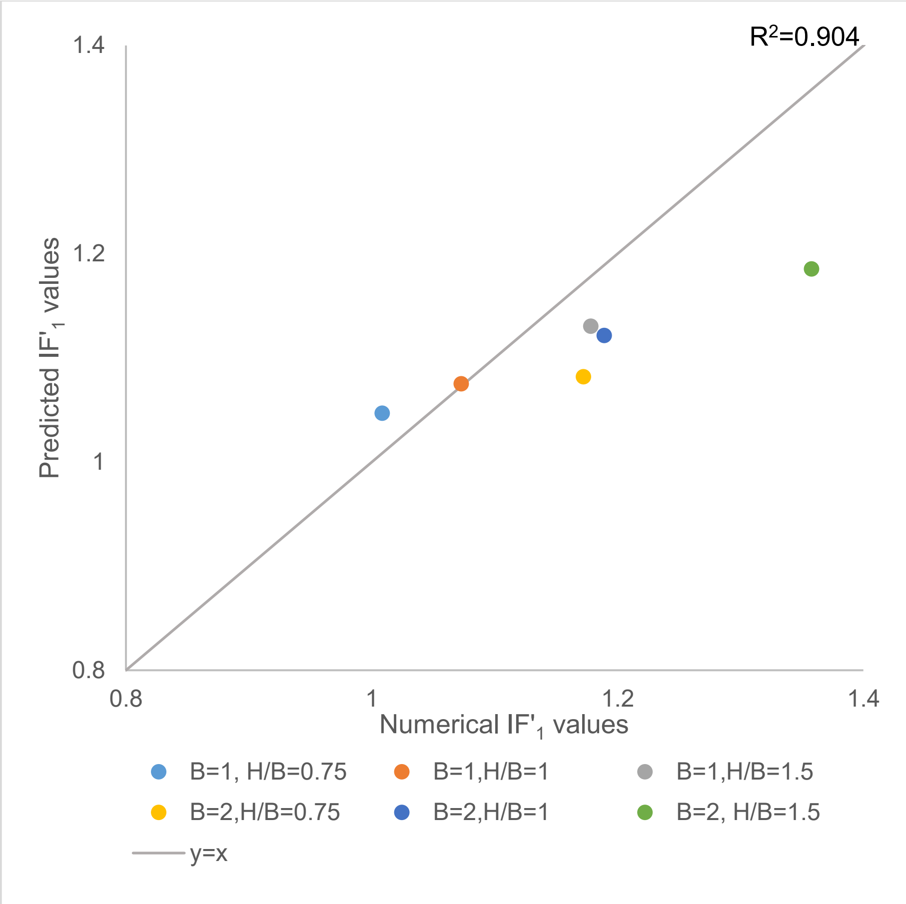


Figure 5.10. Comparison between predicted values of interference factor (IF'_1) using proposed analytical model and numerical analysis for interfered footing

5.4. ANALYTICAL MODEL OF THREE ADJACENT STRIP FOOTINGS ON GRANULAR BED (GB) OVERLYING CLAY [WITH NO VOID AND SIMULTANEOUSLY LOADED]

5.4.1. Analytical Model to Predict the Load Carrying Capacity of the Middle Interfered Footing and Interference Factor

In the case of three adjacent strip footings on GB overlying clay and simultaneously loaded (Figure 5.11), an analytical model is proposed to predict the ultimate bearing capacity of the middle interfered footing at optimum spacing (S/B=1.5). The footing at the centre is under the interference effect from both the footings on either side. Bearing capacity behaviour of middle footing is being studied. It is a further extension/modification of the punching shear model for a two-strip footing on granular bed overlying clay, as explained earlier in section 5.3.

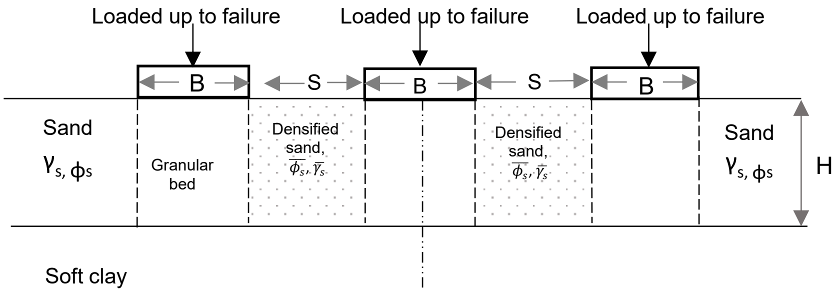


Figure 5.11. Adjacent three-strip footings on granular bed overlying weak soil

The granular soil mass that are present on either side of the middle footing are assumed to be densified to the maximum with increased density $\overline{\gamma_s}$ and increased friction angle $\overline{\phi_s}$ (Figure 5.12). With this modified density and friction angle, mobilised shear resistances, τ'_f developed on the two vertical planes, on either side of the strip footing, are of the same magnitude and are estimated similar to Equation 5.13. Thus, the bearing capacity of middle interfered footing in case of three adjacent strip footings on granular bed overlying weak soil is calculated by Equation 5.17.

$$Q_{ui} = q_{ui}\text{B} = q_{uc}\text{B} + (2\,\tau'_f)\,\text{H} \leq q_s\text{B} \qquad (5.17)$$

The comparison between the values of bearing capacity and interference factor predicted by the proposed modified analytical model, and finite element analyses for middle interfered strip footing on GB overlying weak soil are presented in Tables 5.4-5.5 and figures 5.13-5.14. The ultimate bearing capacity values estimated by the analytical model are in very good agreement with results of numerical analysis (maximum error of 13.29% and average error of about 5.3%). Even the IF'_1 values agree reasonably well.

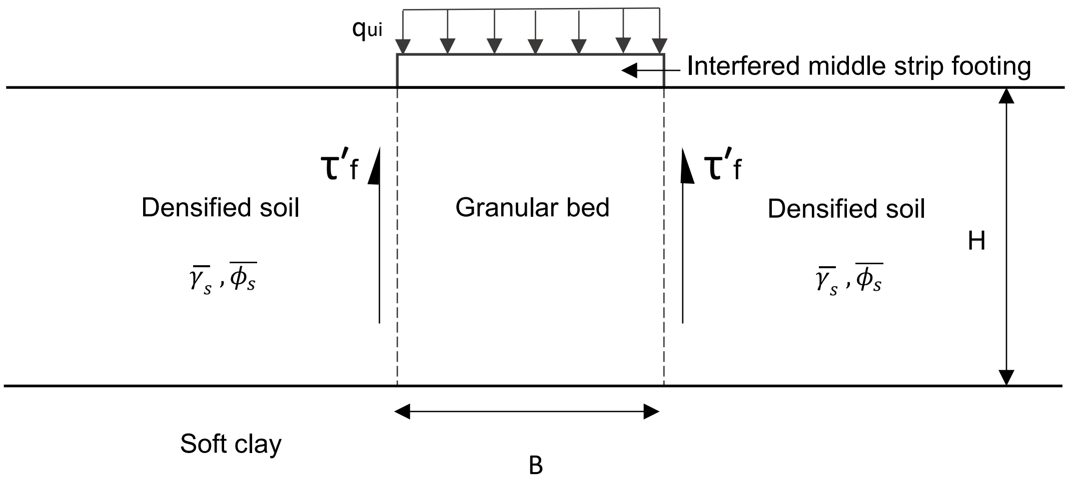


Figure 5.12. Proposed analytical model for the middle interfered footing for three adjacent strip footings on granular bed overlying weak soil

Table 5.4. Predicted and numerical ultimate bearing capacity values for the middle interfered strip footings on granular bed overlying weak soil (Three footings case)

B (m)	H (m)	q_c (1) (kPa)	τ'_{f1}	Δq_{SL} (2)	Proposed analytical model q_{ui} (kPa) (1)+(2)	Numerical analysis q_{ui} (kPa)	Percentage error
1	0.75	102.8	14.53	29.07	131.87	130	1.44
1	1	102.8	25.84	51.67	154.47	148	4.37
1	1.5	102.8	58.13	116.27	203.84	197	3.47
2	1.5	102.8	58.13	58.13	160.93	160	0.49
2	2	102.8	103.35	103.35	206.15	190	8.50
2	3	102.8	232.54	232.54	335.34	296	13.29

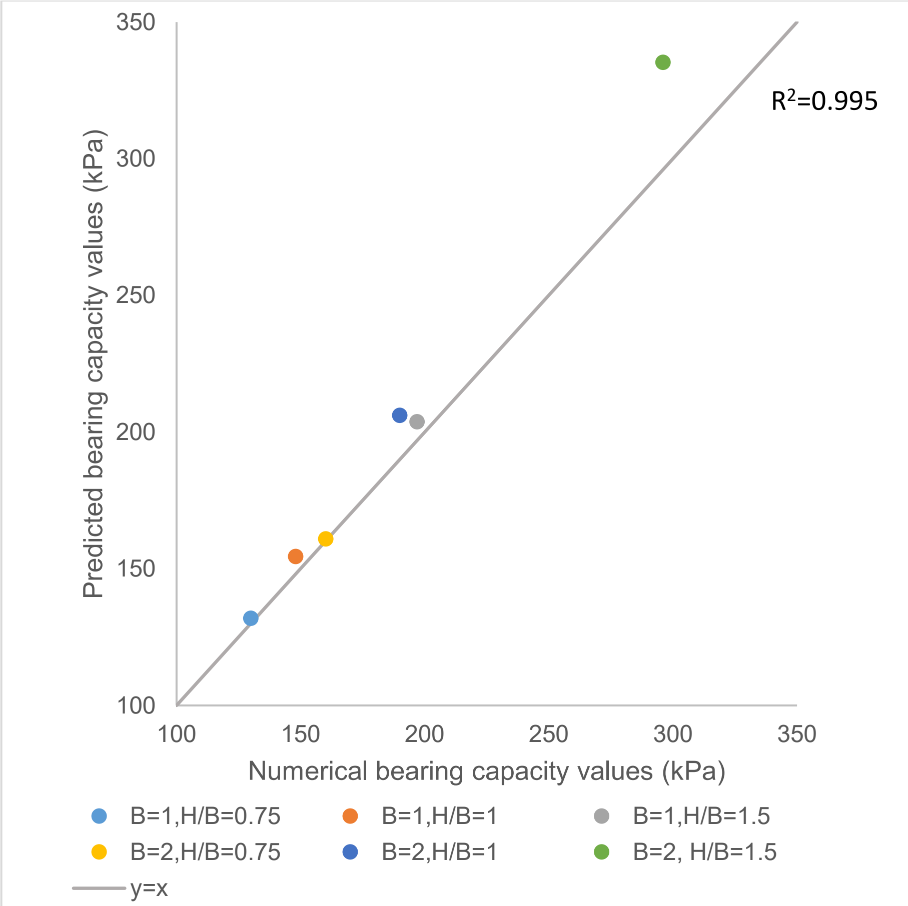


Figure 5.13. Comparison between predicted values of ultimate bearing capacity from 'proposed analytical model for middle interfered footing with numerical studies

Table 5.5. Predicted and numerical interference values for middle interfered strip footing on granular bed overlying weak soil

Specification		Proposed analytical model, q_u (kPa)		Numerical analysis, q_u (kPa)		Interference factor, IF'_1		Percentage error
B (m)	H (m)	Single footing q_{u0}	Interfered Footing, q_{ui}	Single footing, q_{u0}	Interfered Footing, q_{ui}	Proposed model	Numerical analysis	
1	0.75	120.53	131.87	118	130	1.09	1.10	-0.69
1	1	134.32	154.47	137	148	1.15	1.08	6.46
1	1.5	173.72	203.84	157	197	1.17	1.25	-6.49
2	1.5	138.26	160.93	145	160	1.16	1.10	5.39
2	2	165.84	206.15	169	190	1.24	1.12	10.57
2	3	244.64	335.34	218	296	1.37	1.36	0.95

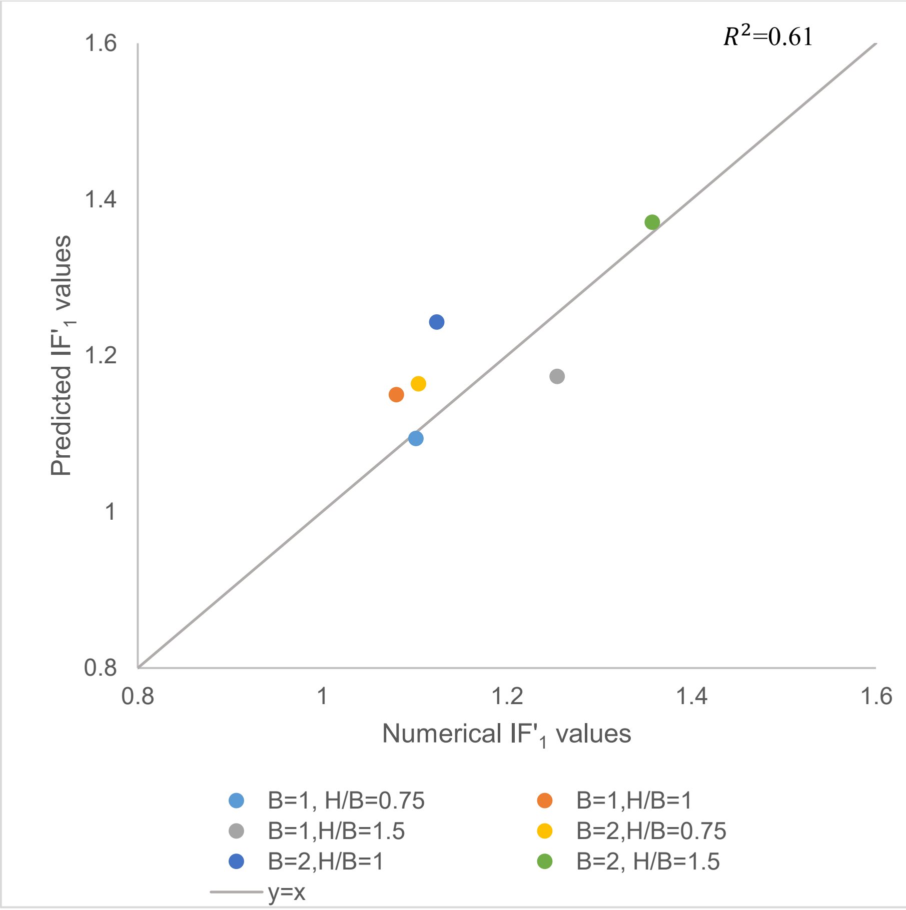


Figure 5.14. Comparison between predicted values of interference factor (IF'_1) using proposed analytical model and numerical analysis for middle interfered footing

5.4.2. Analytical model to predict the load-carrying capacity of the outer interfered footing and interference factor

Footings that are located to the left and right of the middle strip footing are considered as outer interfered footings (Figures 5.15-5.16). The bearing capacity of these footings can be calculated by the 'proposed analytical model for interfered footing' (similar to two adjacent strip footings). Predicted and numerically evaluated ultimate bearing capacity and interference factor values for the left and right-side interfered strip footings on granular bed overlying weak soil for the three footings case, are shown in Table 5.6-5.7 and figures 5.17-5.18. There is good agreement between the two sets of values.

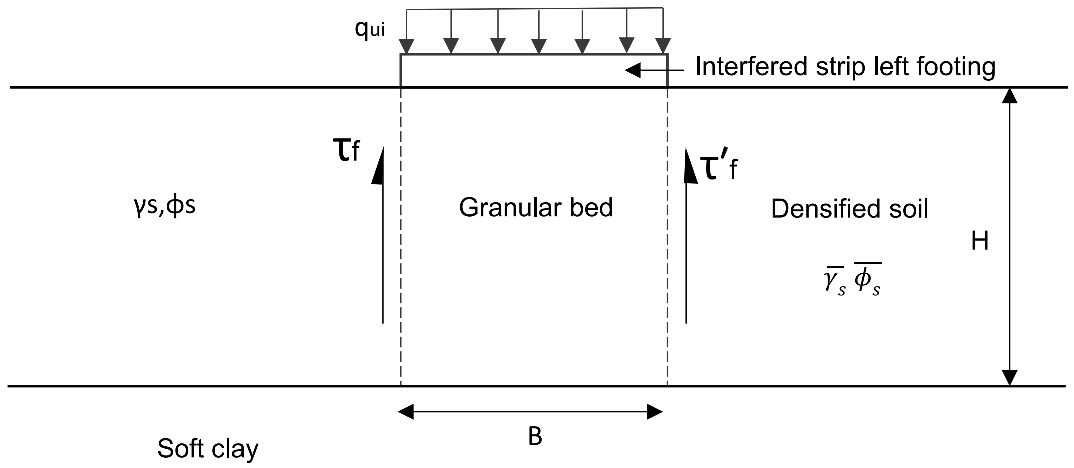


Figure 5.15. Proposed analytical model for the outer left side interfered footing when there are three adjacent strip footings on granular bed overlying weak soil

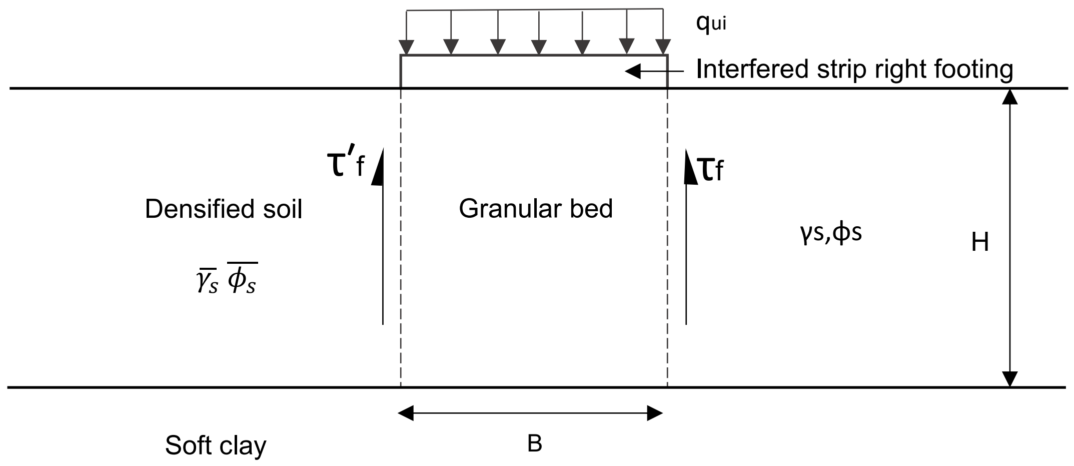


Figure 5.16. Proposed analytical model for the outer right side interfered footing when there are three adjacent strip footings on granular bed overlying weak soil

Table 5.6. Predicted and numerical ultimate bearing capacity values for the left and right-side interfered strip footings on granular bed overlying weak soil (Three footings case)

B (m)	H (m)	q_c (1) (kPa)	τ_f	τ'_f	Δq_{SL} (2)	Proposed analytical model q_{ui} (kPa) (1)+(2)	Numerical analysis q_{ui} (kPa)	Percentage error
1	0.75	102.8	8.87	14.53	23.40	126.20	128	-1.41
1	1	102.8	15.76	25.84	41.60	144.40	147	-1.77
1	1.5	102.8	35.46	58.13	93.59	196.39	198	-0.81
2	1.5	102.8	35.46	58.13	46.80	149.60	161	-6.81
2	2	102.8	63.04	103.35	83.20	186.00	180	3.48
2	3	102.8	141.84	232.54	187.19	289.99	298	-2.69

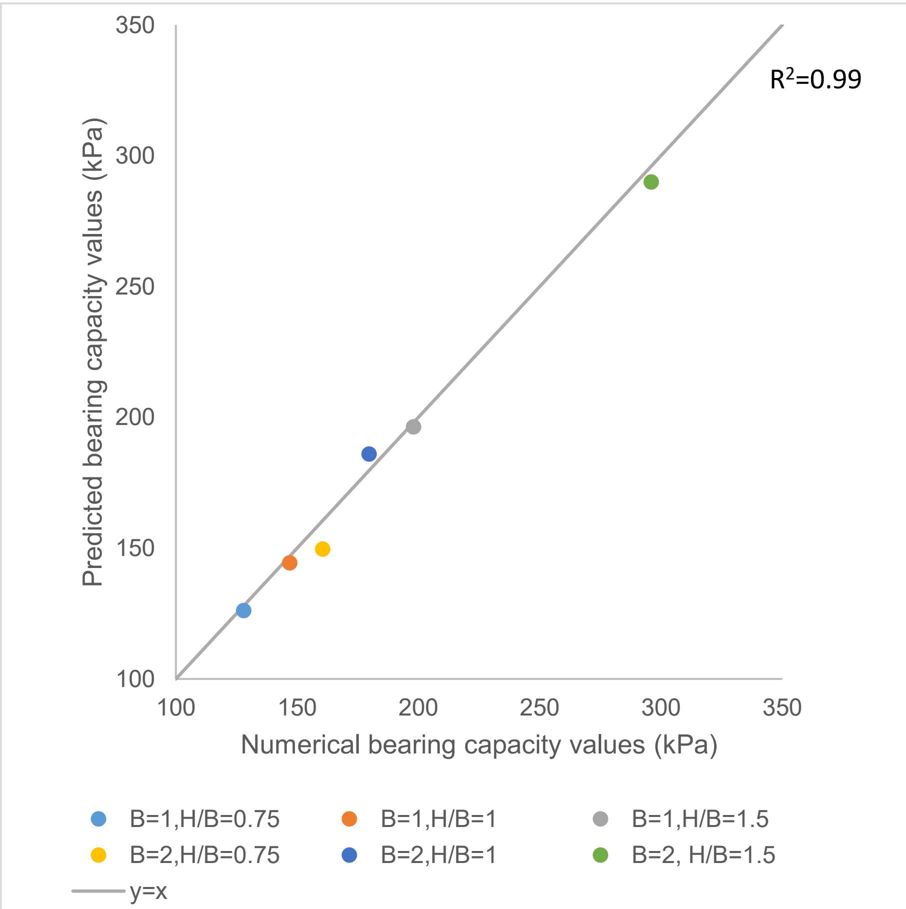


Figure 5.17. Comparison between predicted values of ultimate bearing capacity from 'proposed analytical model' for outer interfered footing with numerical studies

Table 5.7. Predicted and numerical interference values for the left and right side interfered strip footings on granular bed overlying weak soil (Three footings case)

Specification		Proposed analytical model, q_u (kPa)		Numerical analysis, q_u (kPa)		Interference factor, IF'_1		Percentage error
B (m)	H (m)	Single footing q_{u0}	Interfered Footing, q_{ui}	Single footing, q_{u0}	Interfered Footing, q_{ui}	Proposed model	Numerical analysis	
1	0.75	120.53	126.20	118	128	1.05	1.08	-3.48
1	1	134.32	144.40	137	147	1.08	1.07	0.19
1	1.5	173.72	196.39	157	198	1.13	1.26	-10.36
2	1.5	138.26	149.60	145	161	1.08	1.11	-2.27
2	2	165.84	186.00	169	180	1.12	1.06	5.45
2	3	244.64	289.99	218	296	1.19	1.36	-12.70

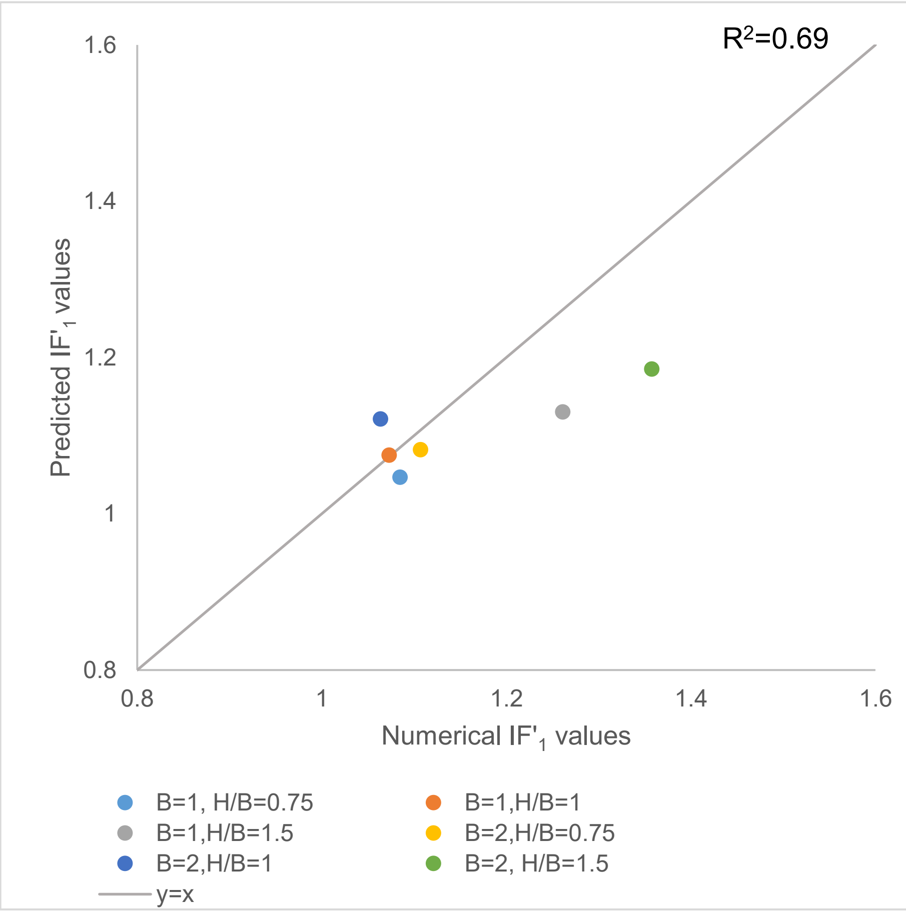


Figure 5.18. Comparison between predicted values of interference factors from 'proposed analytical model' for outer interfered footing with numerical studies

CHAPTER 6

TWO ADJACENT STRIP FOOTINGS ON DIFFERENT TYPES OF SOILS

6.1. GENERAL

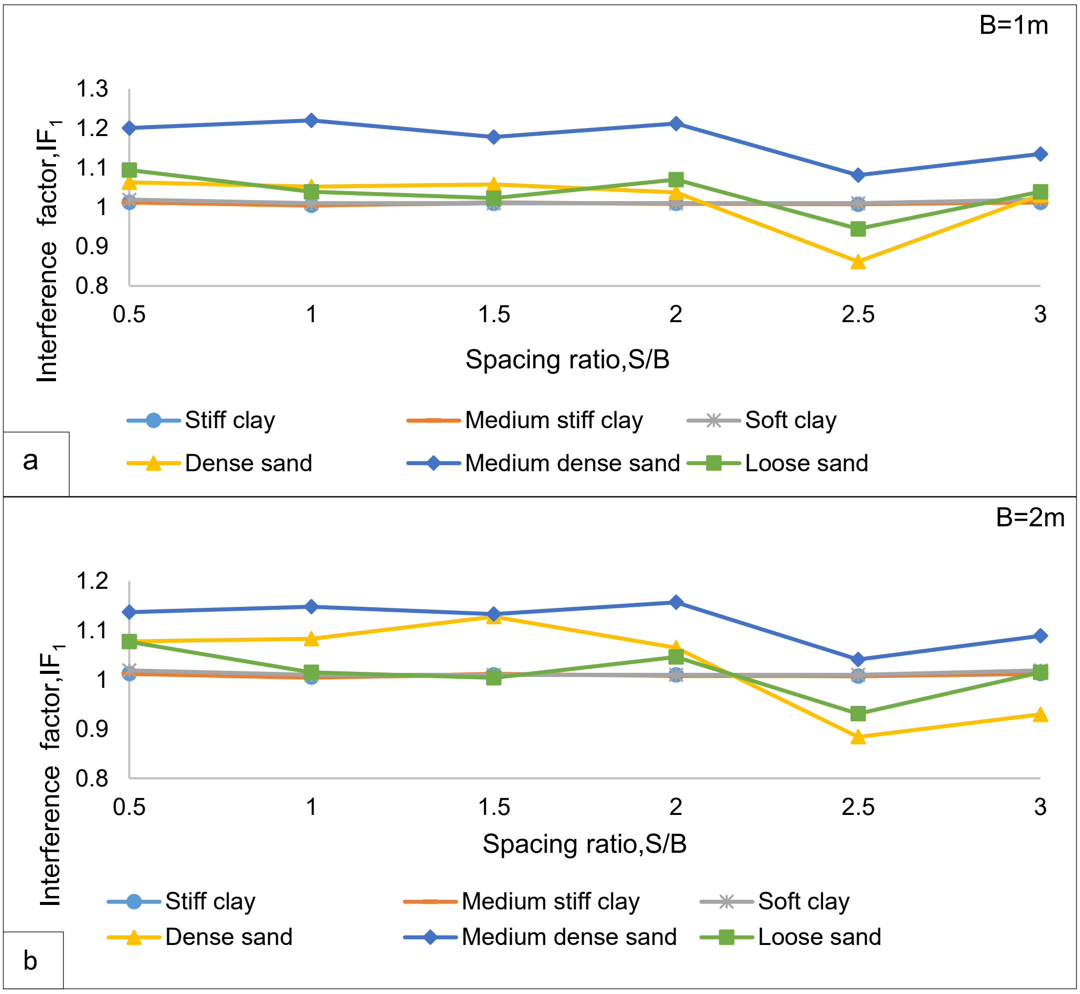
Two adjacent strip footings on sands (loose, medium and dense sands) and clays (soft, medium and stiff clays) are numerically investigated to study the effect of type of soil on the interference effects. The effect of interference, regarding the interference factor for bearing capacity, in the case of clays, is found to be negligible. Providing a shear key beneath the footing centre has a considerable effect on settlements and tilts in the case of clays (Anaswara et al. 2019).

6.2. TWO ADJACENT STRIP FOOTINGS ON DIFFERENT TYPES OF SOILS

Numerical investigations are carried out with various soils and mainly focused on bearing capacity, settlement and tilt characteristics. The soil parameters assigned are shown in Table 6.1. The widths of footings considered are 1m, 2m and 3m. Modulus of elasticity, E of concrete is taken as 25 x10^6 kN/m^2. The thickness of footing, d is taken as 0.75m and Poisson's ratio, υ is considered as 0.15. The footings are modelled to rest on soils and loaded up to the failure. The interference factors, IF_l are determined from bearing pressure-settlement plots. Figure 6.1 shows the variation of interference factor IF_1 with spacing ratio S/B on various soils for footing width 1m, 2m and 3m respectively. Stiff clay, medium-stiff clay and soft clay show that the ultimate bearing capacity of interfering footings compared to isolated footings is not very much different, and there is no significant improvement in bearing capacity. In cohesionless soils, the variation of interference factor shows the same trend for different footing widths. Maximum improvement regarding bearing capacity occurred in the medium dense sand at S/B=2 (20% improvement in case of footing width 1m, 15% in case of 2m wide footing and 11% in case of 3m wide footing respectively).

Table 6.1 Material properties of soils (Bowels (1982))

Parameter	Stiff clay	Medium stiff clay	Soft clay	Dense sand	Medium dense sand	Loose sand
Unit weight, γ (kN/m^3)	18.4	17.2	16.0	19.1	18.2	17.4
Young's modulus, E (kN/m^2)	60000	30000	6000	50000	30000	15000
Poisson's ratio, υ	0.21	0.28	0.35	0.25	0.28	0.30
Cohesion, c (kN/m^2)	80	50	20	0	0	0
Angle of internal friction, φ (^{0})	0	0	0	40	35	30



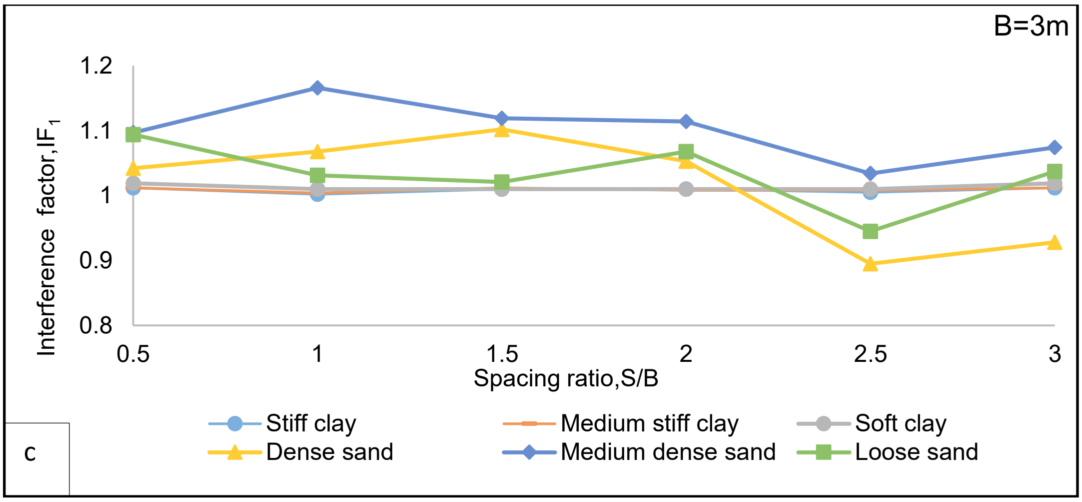


Figure 6.1. Variation of Interference factor IF_1 with S/B on soils for footing widths (a)B=1m (b) B=2m (c) B=3m

To study the interference effect of closely spaced strip footings, efficiency factors due to the settlement are determined from the bearing pressure-settlement plots; where the efficiency factor due to settlement (ξ_δ) is expressed in Equation 6.1. The points considered in the analysis of settlement (a, b, c, d, e, and f) are midway between the footings (Figure 6.2). The efficiency factor is recorded the highest values at the surface point 'a' in most of the spacing ratios. Figure 6.3 shows the variation of the efficiency factor due to settlement (ξ_δ) to the spacing ratio for various footings widths for medium dense sand.

$$\xi_\delta = \frac{\textbf{Settlement at the point considered when two footings are loaded till failure}}{\textbf{Settlement at the point considered when only one footing is present}} \quad (6.1)$$

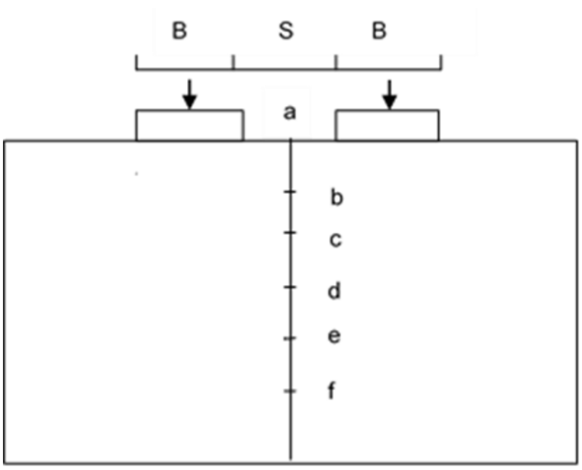


Figure 6.2 Definition of problem

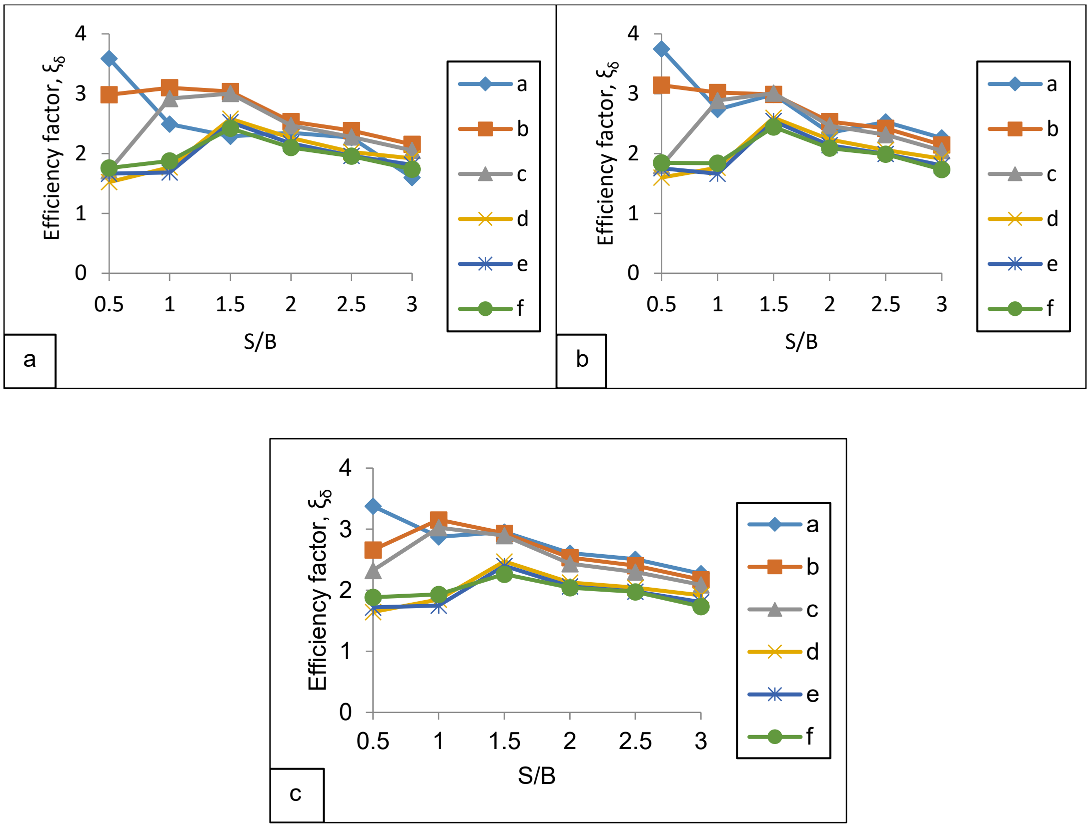


Figure 6.3. Variation of efficiency factor (ξ_δ) with S/B for medium dense sand (a) B=1m (b) B=2m (c) B=3m

Variation of tilt, in percentage, to the spacing ratio is plotted for various footing widths (Figure 6.4). In all six soils, soft clay provides maximum tilt for footing widths of 1m, 2m, and 3m (7 % in footing width 1m, 12% in 2m and 14 % in 3m). It can be observed that the maximum tilt of footing occurs at a spacing ratio of 1.5 in clays and loose sand. It is also observed that maximum tilt at left, as well as right footing, occurs at a spacing ratio of 2 in the case of dense sand and medium dense sand. (1.6 %, 3.2% and 4.8 % of dense sand at spacing ratio 2 for footing width 1m, 2m, and 3m). It is noted that the magnitude of the tilt is proportional to the footing width.

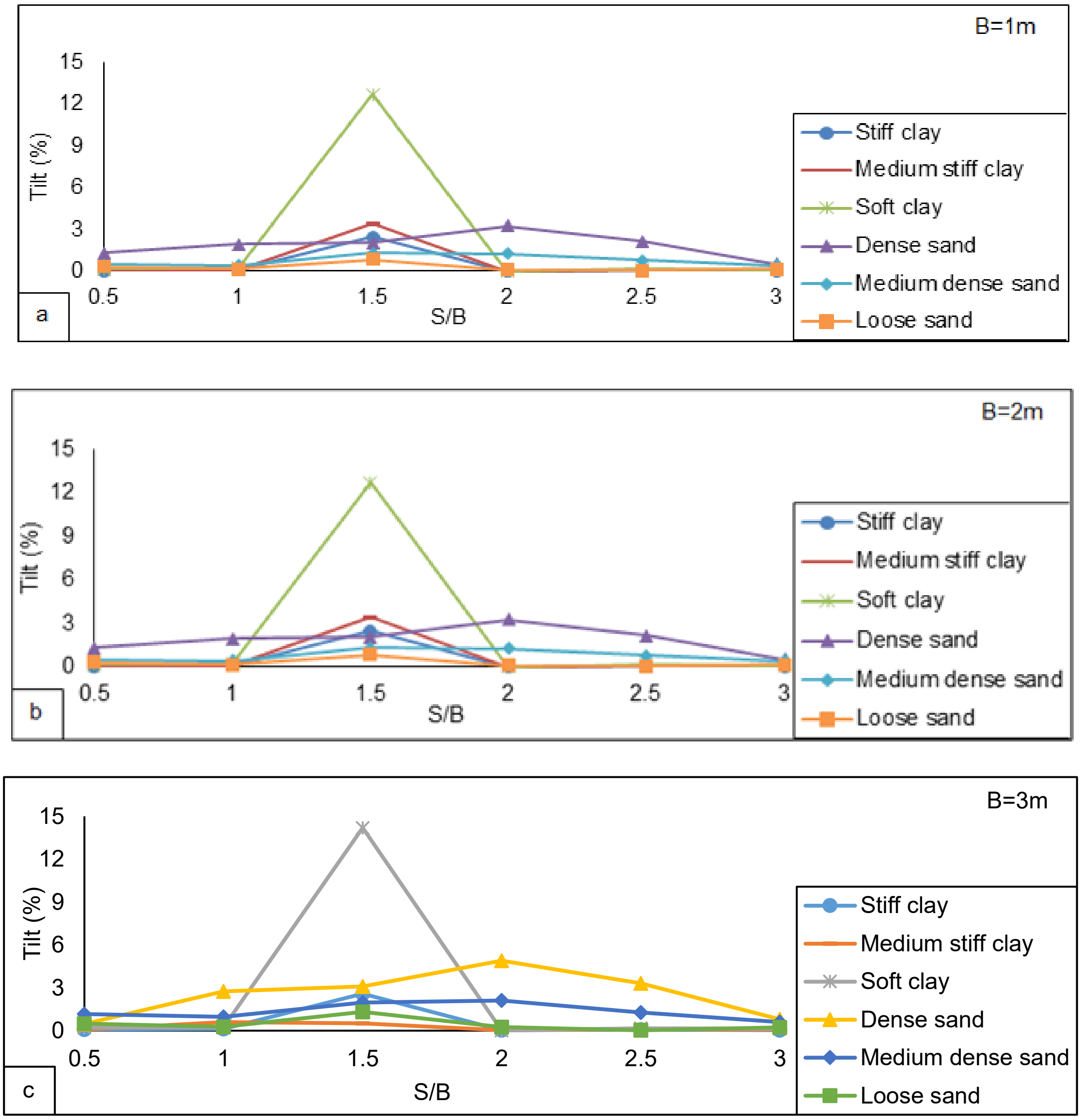


Figure 6.4. Variation of tilt of footing with S/B on soils with footing widths (a) B=1m (b) B=2m (c) B=3m

6.3. EFFECT OF SHEAR KEYS PLACED BENEATH THE FOOTINGS, AT DIFFERENT LOCATIONS BENEATH THE FOOTING AND THE INTERFERENCE OF SUCH FOOTINGS

Shear keys are protrusions provided beneath the footings (Figure 6.5), generally provided to give additional sliding resistance (especially to lateral loads). In the present study, shear keys are contributed to be provided beneath footings to see if they made any difference to the interference effects between the adjacent strip footings subjected to vertical loads. Shear keys are considered to be provided at the inner edge of footings and also at the centre of the footings (Figure 6.5). A parametric study is carried out by varying the L/B ratio of the shear key, where L is the depth of the shear key and B is the width of the footing.

The effect of the shear key on the interference of footing is not significant regarding bearing capacity. Figure 6.6 shows the variation of the settlement of footing when the shear key is added to the footings for footings on stiff clay having B=1m, 2m, and 3m respectively for a spacing ratio of 1.5. From the study, it is found that the settlement becomes less when the shear key placed at the centre of the interfering footings at an L/B ratio of 0.25 irrespective of the footing width. For B=1m the settlement becomes 15% of the settlement of footings without a shear key at the ground surface. In the case of B=2m and B=3m settlement becomes almost 25% of footings without a shear key. The tilt of footing decreases drastically when the shear key included in the footing. The reduction in the tilt of footing is more than 90% of the tilt of footing without a shear key (Table 6.2).

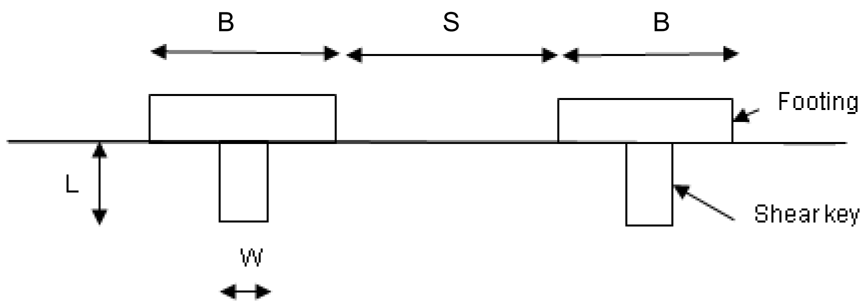


Figure 6.5. Footings with the shear key at the centre

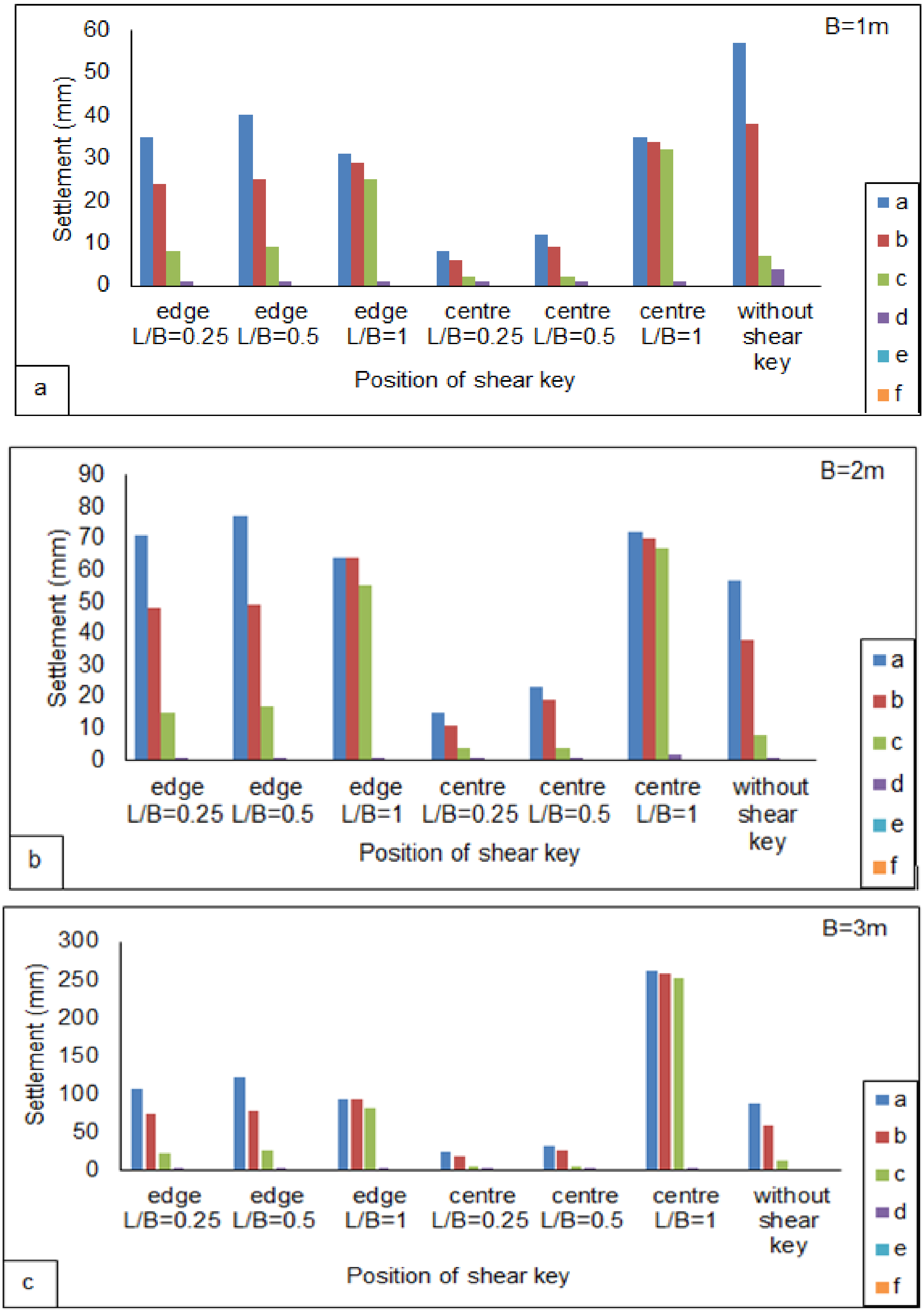


Figure 6.6. Variation of the settlement of footing with (placed at edge and centre of footing) and without shear key on stiff clay for a spacing ratio of 1.5 with footing width (a) B=1 m (b) B=2m (c) B=3m

Table 6.2. Variation of tilt with and without the shear key on footings for footings resting on stiff clay

Footing width (m)	Tilt (%)	
	Footings without shear key	Footings with the shear key at centre L/B=0.25
1	5.304	0.202
2	2.515	0.214
3	2.585	0.230

6.4 INTERFERENCE STUDY BETWEEN A RETAINING WALL AND A CLOSELY BUILT STRIP FOOTING

A footing is considered placed adjacent to a (reverse) L-shaped retaining wall. The ratio between the length of the base (B) to the stem height of the retaining wall (H), B/H lay between 0.5 and 0.8 is reasonable as far as the equilibrium between rotation and translation of the wall is concerned (Rouili 2013). B/H=0.8 is selected for this study. The retaining wall height is fixed as 4m. The base of the retaining wall is maintained 0.8H width and considered to be constructed 1m below from ground surface. The base of the retaining wall is acting as a footing with width B. A shear key having depth (L) 0.25B, 0.5B and 1B are included in the retaining wall base at the centre and junction between stem and base.

A building is being constructed close to the retaining wall (Figure 6.7). A strip footing with a width of 3m supporting the building is considered. The interference effect of the base of the retaining wall acts as old footing and strip footing as the new footing is considered. Strip footing of 0.75m thick and 3m width spaced at a spacing ratio (S/B) equal to 0.5 and retaining wall are considered to be placed on loose sand. The footing is loaded up to safe bearing capacity (Factor of safety is taken as 3). The footings are loaded unequally and sequentially to simulate the situation like old and new footings. An additional element shear key is considered to be added in the retaining wall base at the centre and the junction between the stem and base of the retaining wall. The parametric study is carried out by varying the L/B ratio of the shear key, where L is the depth of the shear key and B is the width of the base. The objective is to determine the magnitude of settlement and tilt of the base of the retaining wall before and after the building construction and check the effect of tilt on the new footing.

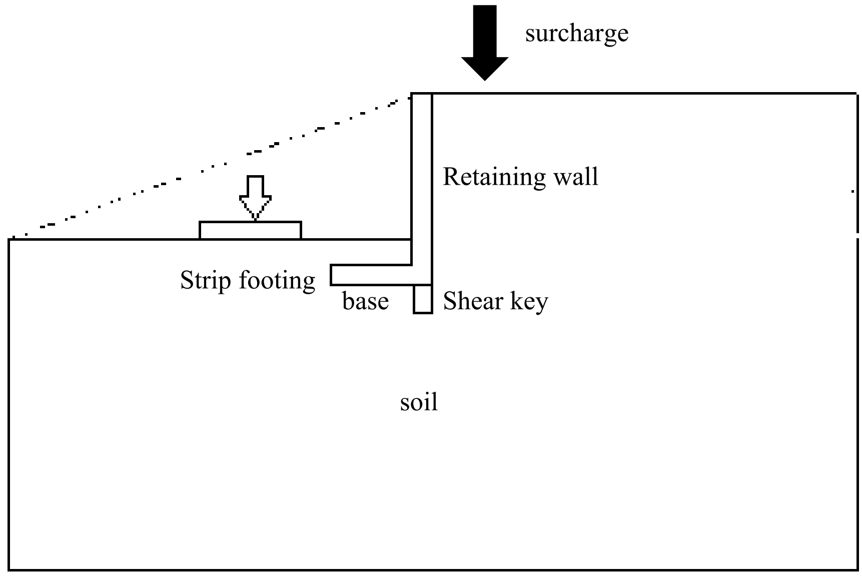


Figure 6.7. L-shaped retaining wall with the shear key adjacent to strip footing

From the analysis carried out for two similar and adjacent strip footings without the shear key on loose sand, it is found that the settlement and tilt are maximum at a spacing ratio of 0.5 (Figures 6.8, 6.9). The shear key is considered to be provided at the below junction and below the centre of the base with a surcharge of 20 kN/m^2. Shear key provided at the junction between base and stem of retaining wall with L/B=1 reduces settlement and tilt by 41% and 60% respectively (Figures 6.8, 6.9).

Figure 6.8. Settlement of base of retaining wall before and after the construction of new footing

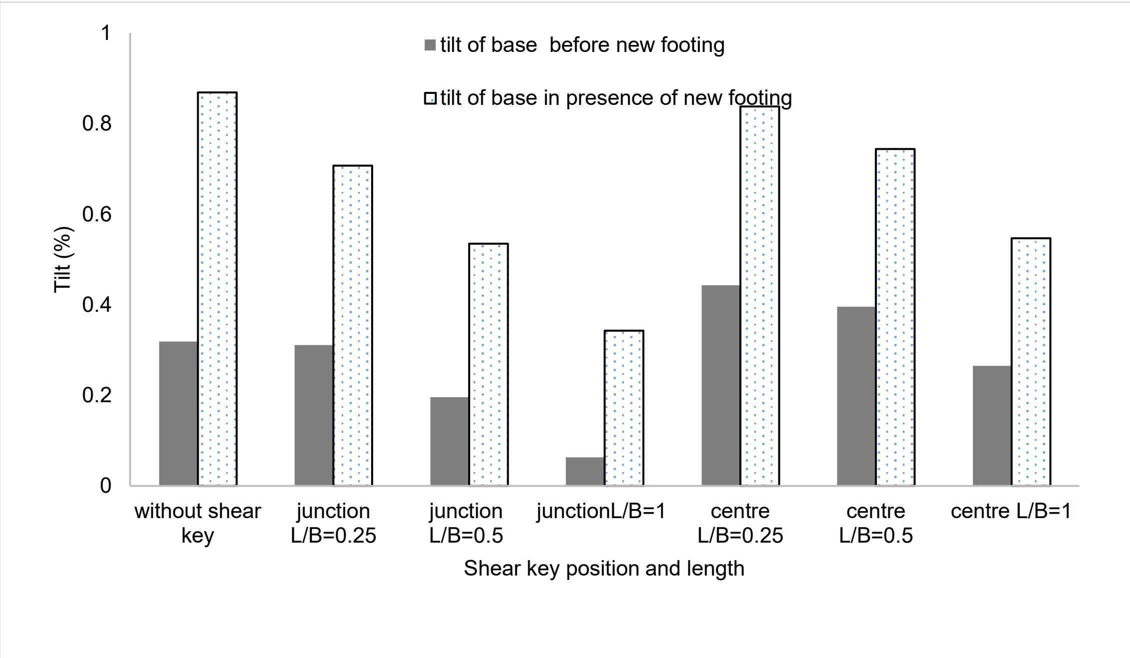


Figure 6.9. Tilt of base of retaining wall before and after construction of new footing

CHAPTER 7

CONCLUSION

7.1. GENERAL

The conclusions of this research work are discussed in this chapter. The interference effect of strip footings are studied, and the conclusions are summarised. The variation of bearing capacity, settlement and tilt are studied under different conditions, and the conclusions are stated in this chapter. The conclusions from the results of experimental studies, numerical analyses and analytical studies studying the effect of interference on granular soil and granular bed overlying weak soil are summarised in this chapter.

7.2. CONCLUSION

7.2.1. Experimental and Numerical Interference Studies of Adjacent Strip Footings on Unreinforced and Reinforced Medium Dense Sands

Experimental and numerical studies are carried out on closely spaced strip footings, resting on the surface of the sand, to study the effects of interference. The study is conducted at different spacings; from S/B=1 to 4 where S is the clear spacing between the footings and B is the width of the footing and different loading conditions. Experimental and numerical studies are carried on two widths of footings 50 mm and 100 mm, on unreinforced and reinforced foundation soils. Simultaneous and sequential loading on the footings are considered in this study.

'Interference' affects stresses in foundation soil, load-carrying capacity of footings, settlements and tilts of footings are being studied. The increment in bearing capacity is a positive effect but settlement and tilt increment are negative effects of interference. Tilts could cause cracks between the wall and the foundation or between the wall and the roof slab.

The following conclusions are drawn from this study

- The bearing capacity of the footing generally peaks at a certain optimum spacing between the footings. At S/B=2, the interference effect improves the bearing capacity of the 50mm and 100mm footings by 37% and 74%, respectively.

- The settlement of the footing is expressed in terms of interference factor (ξ_δ), and it also attains its peak value (ξ_δ= 1.31) at around S/B=2 in the case of two adjacent strip footings.
- Due to the interference effect, the confining pressure of the foundation soil between the two adjacent footings increases, due to the loads on the two adjacent strip footings. The foundation soil between the footings becomes stiffer, and this also influences the tilts of the footings.
- The tilts of footings decrease with an increase in spacing between the footings. On unreinforced soil, increasing the distance from 1B to 4B between the footings results in a nearly 12% reduction in tilt in interfered footing. In the case of reinforcement under both the footings and simultaneously loaded, the effect of reinforcement is significant in reducing the tilt of footings. At S/B=2, introducing three reinforcing layers beneath simultaneously loaded interfering footings results in a 2.6 percent tilt reduction. In the case of sequential loading of old and new footing, providing reinforcement beneath the new footing and loading it to maximum, causes a somewhat larger tilt (6.32% increment) of already existing strip footings.
- The failure mechanism in the case of reinforced foundation soils differs from the unreinforced case. Failure surfaces emerge from beneath the reinforcement layers, and it is broader and deeper.
- For three adjacent strip footings resting on unreinforced soil with simultaneously loaded, the maximum interference factor (IF_I=1.26) is obtained at a spacing of S/B=1. It is found that the tilt of the centre footing is very less.

7.2.2. Study on Behaviour of Two Adjacent Strip Footings on Granular Bed Overlying Clay with A Void

In the present study, numerical analyses are carried out to determine the bearing capacity behaviour of single and two adjacently placed strip footings, on GB overlying weak soil, with and without voids. Simultaneous and sequential loading of the two footings are considered in this study.

The following conclusions are drawn from this study

- The bearing capacity increases with the thickness of the granular bed (H/B) up to an optimum thickness (H/B=2) and thereafter remains constant for footing on GB overlying weak soil.
- With two adjacent strip footings on GB overlying weak soil, the bearing resistance of each footing is more than (14% for B=1m and 36% for B=2m at S/B=1.5 and H/B=1.5) than a single independent strip footing on GB overlying weak soil. This is true for all thicknesses of granular bed (H/B ratios of 0.75-2.0), and spacings (S/B ratios of 1.0-3.0) studied. The bearing resistance of the footings peaks at a specific critical spacing between the footings. The peak value of the interference factor (IF'_1) is obtained at about S/B=1.5 for 1 m and 2 m wide footings in the case of simultaneous loading. In the case of unequal and sequential loading, the IF'_2 value peaks at about S/B=3.
- The formation of voids beneath footings reduces the load-carrying capacity of the footings. In the case of a single void under two footings, the maximum reduction in bearing capacity of new footing (53% reduction for B=1m, H/B=1) is reported when the void is formed directly below the new footing.
- The effect of a single void in reducing the bearing capacity is insignificant when the void is present below a critical depth which is more than 5B, and if the void is located at a lateral distance of more than 3B from the centreline of the footing.
- When a void is formed anywhere beneath the footing/s in the weak soil (either directly beneath or nearby/close to the centre line of the footing/s), failure surfaces developed from the nearest footings tend to move towards the void and are found to be narrower than the no void case.
- In the case of two closely spaced and adjacent strip footings on granular bed overlying a weak soil, with a void in the weak soil, the reduction in the bearing capacity due to the presence of void is somewhat compensated by the interference phenomenon between the two footings.

7.2.3. Study on Behaviour of Two Adjacent Strip Footings on Reinforced Granular Bed Overlying Clay with Voids

In the present study, numerical analyses are carried out to determine the bearing capacity behaviour of single and two adjacently placed strip footings, on GB/RGB overlying weak soil, with and without voids. Simultaneous loading of the two footings is considered in this study.

- Providing a reinforced granular bed (RGB) over clay is an effective method to counter the effects of void in the clay. Providing a continuous reinforcement beneath the two adjacent strip footings on RGB over clay with a void is shown to perform better as compared to discontinuous reinforcement. In the case of footing on RGB over clay with voids, there is the combined 'Interference effect' and 'Reinforcement effect' (42% increment in bearing capacity). This combined effect can effectively and substantially counter the negative effects due to the void formation, i.e., reduction in bearing capacity.

7.2.4. Analytical Model to Predict Bearing capacity and Interference Factor

An analytical model for the prediction of the bearing capacity and the interference factor of adjacent strip footing on granular bed overlying weak soil is developed.

- A punching shear failure mechanism is envisaged in the analytical model.
- The increase in bearing capacity is attributed solely to the shear layer effect of the upper granular layer. Numerical studies establish that the granular layer between the two adjacent strip footings are laterally confined to the maximum at the optimum spacing between the footings.
- The values of bearing capacity and interference factor predicted by the proposed analytical model are in reasonably good agreement with those obtained from finite element and experimental studies.

7.2.5. Two Adjacent Strip Footings on Different Types of Soils

Two adjacent strip footings on sands (loose, medium and dense sands) and clays (soft, medium and stiff clays) are numerically investigated to study the effect of type of soil on the interference effects.

- The effect of interference, regarding the interference factor for bearing capacity, in the case of clays is negligible.
- The effect of the shear key on footings resting on stiff clay seems to be maximised when the shear key is placed at the centre of the footing having an L/B ratio of 0.25.
- The settlement decreases drastically, compared to the interfered footings without a shear key for the same conditions. Moreover, the reduction in the settlement is in the range of 75%.
- The tilt of footing on stiff clay reduces by the addition of a shear key on footings. The reduction is in the range of 90%.
- The shear key provided beneath the junction of base and stem of the retaining wall is efficient in reducing tilt and settlement of base of retaining wall in addition to providing better resistance to sliding forces.
- Shear key provided at the junction between base and stem of retaining wall with L/B=1 reduces settlement and tilt by 41% and 60% respectively.

7.3. MAJOR CONTRIBUTIONS OF THIS RESEARCH WORK

The major contributions of this research work are:

- From a series of laboratory-scale plate load tests carried out to study the interference effects on strip footings placed adjacent to each other on unreinforced/reinforced granular soils, it is established/confirmed that the bearing resistances of the footing/s peaks at a specific critical spacing between the footings.
- The various factors such as the thickness of granular bed, width of footing/s, spacing between the footings, presence of void, reinforcement in the granular bed, type of loading conditions influence the interference effect on adjacent strip

footings on layered soils and thereby affect bearing capacities, settlements, tilts and shear strain contours in foundation soil.

- This study attempts to study interference of adjacent footings which are loaded (i) Equally and simultaneously (ii) Unequally and sequentially, which are very common practical cases.
- In the case of sequential loading of old and new footing, providing reinforcement beneath the new footing and loading it to maximum, causes a somewhat larger tilt of already existing strip footings.
- In the case of two closely spaced strip footings on layered soils, with a void in the weak soil, the reduction in the bearing capacity due to the presence of void is somewhat compensated by the interference phenomenon between the two footings.
- The role of reinforcement in reinforced granular bed (RGB) overlying weak soil in giving support to a set of footings, when voids are present in the weak soil beneath, are very significant.
- A simple analytical model to estimate the bearing capacity and interference factor of interfered footing in the case of two and three adjacent footings is established. The accuracy of the proposed model has verified with finite element simulations and the percentage error is about 13%.

7.4. RECOMMENDATIONS

- The maintenance of optimum depth of granular bed overlying weak soil is beneficial to improve the bearing capacity and reduce settlement beneath adjacent footings.
- It is recommended providing reinforcement beneath the adjacent footings is beneficial in reducing differential settlement and tilt.
- It is recommended to provide continuous reinforcement beneath the two adjacent strip footings on RGB over clay with a void, which is shown to perform better as compared to discontinuous reinforcement.

- It is recommended to provide reinforcement beneath the newly constructed adjacent footings on weak soil where chances of void could be formed in future to avoid the decrease in serviceability of the structure.
- Construction of new footing adjacent to an existing structure may adversely affect the old footing. So extra care should be taken while designing a new footing adjacent to an old footing. The new footing should construct beyond the optimum distance from the existing footing. If possible provide reinforcement below new footing while construction to reduce settlement and tilt.
- The adjacent footings constructed with shear key is placed at the centre of footings with L/B=0.25 is beneficial in reducing settlement and tilt.
- The shear key provided beneath the junction of base and stem of the retaining wall placed adjacent to a building is efficient in reducing tilt and settlement of base of retaining wall in addition to providing better resistance to sliding forces.

7.5. SCOPE OF FUTURE WORK

- The large scale plate load tests on adjacent footings can be performed to study interference effect for different types of footings (such as square, rectangular and circular footings).
- Experimental study of adjacent footings with and without voids (single and multiple voids) can be performed.
- An experimental study of adjacent footings with different loading conditions such as simultaneous and sequential phased loading can be conducted.
- An experimental study of adjacent footings with various reinforcement configurations, i.e. for both continuous and discontinuous reinforcement conditions can be conducted.
- The analytical study can be extended for interference effect on footings with different loading and void cases.
- Numerical analysis can be extended to 3D analyses for various cases

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LIST OF PUBLICATIONS

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2. Anaswara, S., Shivashankar, R. (2020). "Study on Behaviour of Two Adjacent Strip Footings on Unreinforced/Reinforced Granular Bed Overlying Clay with Voids."*Geotechnical and Geological Engineering*, 39(3), 1831-1848. DOI:10.1007/s10706-020-01590-1.

3. Anaswara, S., Lakshmy, G.S., Shivashankar, R. (2020). "Interference studies of adjacent strip footings on unreinforced and reinforced sands*". Transportation Infrastructure Geotechnology,* 7,535–561.DOI:10.1007/s40515-020-00104-z

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6. Anaswara, S., Amrita., Shivashankar, R. (2017). "Numerical analysis on interference of strip footings on soils", *International Journal of Engineering and Advanced Technology.* ISSN:2249-8958 (Online), 7(ICMSC17), 116-119.

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7. Anaswara S., Shivashankar R. (2021). "Study of Tilt on Adjacent Strip Footings". Singh R.M., Sudheer K.P., Kurian B. (eds) *Advances in Civil Engineering. Lecture Notes in Civil Engineering*, 83.Springer, Singapore. DOI:10.1007/978-981-15-5644-9_39.

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2. Anaswara, S., Shivashankar, R. (2019). "Interference study between a retaining wall and a closely built strip footing", *8th International Engineering Symposium-IES 2019*, Kumamoto, Japan.

3. Anaswara, S., Shivashankar, R. (2019). "Interference study between a retaining wall and a closely built strip footing on lateritic soil", *Symposium on laterites and lateritic soils*, Thiruvananthapuram, India.

4. Anaswara, S., Shivashankar, R. (2019). "Study of tilt on adjacent strip footings", *International conference on advanced research and innovations in civil engineering (ARICE) 2019*, Kochi, India.

5. Anaswara, S., Shivashankar, R. (2019). “A Numerical Study on interference effects of closely spaced strip footings on cohesionless soils” *International conference trending moments & steer forces-Civil engineering today (TMSF-2019)*, Goa, India.

6. Anaswara, S., Shivashankar, R. (2019). “Studies on tilt of closely spaced strip footings on unreinforced and reinforced sands” *Indian Geotechnical Conference IGC2019*, Surat, India.

7. P. Hridya, Anaswara, S., Shivashankar, R. (2018). “Numerical study on interference of surface strip footings resting on stiff clay”, *Indian Geotechnical Conference IGC2018*, Bangalore, India.

8. Anaswara, S., Amrita, Shivashankar, R. (2017). “Numerical analysis on interference of strip footings on soils”, *International conference on modelling and simulation in civil engineering-ICMSC 2017*, Kollam, India.

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M.TECH (Geotechnical Engineering)	2015	National Institute of Technology Karnataka	NIT (Institute of National Importance)	9.03
B. TECH (Civil Engineering)	2012	M.A. College of Engineering Kothamangalam	MG University, Kottayam	78%
XII	2008	SNDP H.S.S, Muvattupuzha Ernakulam	Kerala State Board	94.33%
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