Effect of Flexible Void on Ultimate Bearing Capacity of Eccentrically Loaded Shallow Strip Footing on Granular Soil

A Thesis submitted in partial fulfillment of the requirements

for the award of the Degree of

Master of Technology

in

Civil Engineering

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This is to certify that the work presented in the dissertation entitled "Effect of Flexible Void on Ultimate Bearing Capacity of Eccentrically Loaded Shallow Strip Footing on Granular Soil", submitted by *Shubham Rajput*, Roll Number 214CE1072, is a record of original research carried out by him under my supervision and guidance in partial fulfillment of the requirements of the degree of *Master of Technology* in *Civil Engineering*. Neither this dissertation nor any part of it has been submitted earlier for any degree or diploma to any institute or university in India or abroad.

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Assistant Professor

Declaration of Originality

I, Shubham Rajput, Roll Number 214CE1072 hereby declare that this dissertation entitled "*Effect of flexible void on the ultimate bearing capacity of eccentrically loaded shallow strip footing on granular soil*", presents my original work carried out as a master student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections "Reference" or "Bibliography". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

May 26, 2016
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ABSTRACT

Since the development of Terzaghi's theory on the ultimate bearing capacity of shallow foundations in 1943, outcomes of various studies either theoretical, experimental and numerical, done by various investigators has been brought into light. Apart from centric vertical load, various researchers have also studied the effect of eccentric vertical load, centric inclined load and eccentrically inclined load on foundation system. Due to chemical flow, underground pipe lines, mining, blasting and other underground activities, which have dynamic impact on the soil creates flexible voids below the foundation. Nearness of void underneath the footing influences the stability itself and causes serious harm to the structure.

Based on the literature review, it appears that limited research has been carried out in the field of ultimate bearing capacity of shallow foundation, when the foundation is subjected to eccentric vertical load having a void beneath the foundation. The origin of present study targets that scarcity in research.

In order to achieve the objective, one hundred and fifty-six numbers of numerical models have been made using PLAXIS to study the ultimate bearing capacity of shallow strip foundation resting over dry sand bed with the flexible void underneath the footing. The embedment ratio (D_f /B) was varied from zero to one. The eccentricity was varied from 0 to 0.15B (where, B = width of footing) with an increment of 0.05B. The effect of flexible void on the ultimate bearing capacity of the footing has been analyzed by varying the size (D = Diameter of void), location (L = Location of void below foundation base) and horizontal distance (H) of the voids from center line of the footing. Based on the numerical results, three numbers of reduction factors are developed to predict the ultimate bearing capacity of shallow strip footing lying over a void on dry sand bed by knowing the ultimate bearing capacity of footing in the absence of flexible void.

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CHAPTER -1

INTRODUCTION

1.1 Shallow foundation on sand with eccentric loading

All designed civil structures, whether it might be buildings, bridges, highways or rail tracks will surely comprise of a superstructure and a foundation. The basic structural function of the foundation is to receive the load from the superstructure and transmit it securely to the hard soil or bearing strata beneath as per the soil deposits underneath. The design configuration of shallow foundation which includes the plan and sectional measurements of the foundation is being achieved by fulfilling two prerequisites: (a) Bearing Capacity and (b) Settlement. Bearing capacity alludes to the ultimate i.e. the maximum extreme load value, the underlying soil can sustain or manage without undergoing failure under given conditions.

Engineers should have the capability to figure out the foundation capacity of the most basic and frequent case of central vertical loads. This need has prompted to bring more advancement in the speculations and hypothesis of bearing capacity, outstandingly the Terzaghi's method. Prediction of bearing capacity in light of Terzaghi's (1943) superposition technique are somewhat hypothetical and halfway empirical. Various analytical solutions have been proposed for the calculation of those factors

All the bearing capacity estimation techniques are further characterized into the below mentioned four categories:

(1) The limit equilibrium method; (2) The characteristics method; (3) The upper-bound plastic limit analysis and (4) The numerical method in light of either the finite-element technique or finite difference method. The issues can be resolved by two diverse methodologies: experimentally, by considering model or full-scale tests; or, by utilizing numerical approaches, for example, finite element approach. Conducting a full-scale test are the perfect technique for getting reliable results, however, practical issues and monetary issues either dispense or significantly confine the possibility of conducting a full-scale testing. As an option, model test might be utilized, yet they have various shot falls and drawbacks. The outcomes of the conducted model tests are mostly influenced by the boundary limitations of the test tank dimensions, the footing dimensions, the disturbance occurred in the sample, the equipment setup and

methodology. It is profitable to utilize the strategies of numerical techniques to simulate the state of tests conducted to check the theoretical available models. Due to the various advancements in numerical methodology and computer programming, it is beneficial to utilize these systems to simulate the state of model tests to confirm the theoretical models. The theoretical study can then be extended more authentically to cover an extensive variety of field cases which engineers discarded considering the full-scale testing.

The greater part of the studies for bearing capacity computation depends on the foundation under vertical and central loading. However, in other instances because of bending moments and horizontal pressure transmitted from the superstructure, shallow foundations of civil structures like retaining walls, bridge abutments, offshore structures, oil/gas platforms in offshore areas, mechanical instruments, and portal framed structures are in most cases subjected to eccentric loading. This might be because of (a) moments with or without axial forces (b) their area closes to the property line. They can be considered as eccentrically loaded strip footings, with eccentricity of e. Because of load eccentricity, the general stability of foundation gets reduced due to detrimental settlement caused due to differential loading and foundation tilting which lessens the bearing capacity.

The bearing capacity estimation of foundations under eccentric loading is of immense significance in geotechnical engineering. In order to have further advancement in the current research, extensive reviews of various literatures have been done to narrow down the scope of present study. Enhanced investigations and analysis are displayed in the upcoming chapters for evaluating ultimate bearing capacity of shallow strip footing subjected to eccentric load resting on a dry sand bed.

1.2 Footing over voids

The bearing capacity will change with the existence of minerals in soil, with level of water table and with proximity of cavities or voids in soil. Presence of underground void influences stability of rigid surface structures, for example, foundations, rigid pavements over passages and underground pipe lines. Furthermore, the fundamental integral stability of structure. Void may exist precisely beneath the foundation or at any area inside the critical region i.e. the region covered under the pressure bulb, it influences stability of footing.

From numerous geotechnical and geological studies on the causes and the regions at which voids or cavities formed are as follows:

- In a few areas mining activities like blasting etc. causes dynamic loads in soil leads to the development of underground voids.
- Construction of tunnels, reservoir conduits, channels, underground water tanks and storm or sewer lines in the urban region to achieve the utilities of developing population.
- The materials, for example, salts, dolomite, gypsum and lime stone forms mixture by chemical reaction with water or other reagents. The space came about because of the flow of this liquid structured various cavity at more prominent frequency inside the ground.
- Cavities may be developed in lieu of lithology of rocks and soils.
- Most of voids happens in Calcareous silt in light of their high crushable property and disintegration which is related to flow direction of underground water.
- Methane hydrate is a vital constituent in sedimentary rocks of Polar Regions. In methane hydrate extensive measure of methane caught in crystal stone structure of water forms ice like solid. Separation of this because of temperature changes and different reasons causes voids formation.
- In storage reservoirs spillage of any substance causes formation of voids.
- Due to differential settlement of structures, municipal solid waste, ineffectively compacted backfill and tension cracks in unsaturated cohesive soils, breakdown of underground structures, for example, tunnels, marine subways, tanks and pipes.
- Existence of cracks and faulty planes in jointed rock mass results into voids.
- From past studies it is demonstrated that the roads in north need to cross territories containing ice wedges, because of warm attributes of the road surface solidifying and defrosting of ice takes, which results in arrangement of gaps and plunges on or under the surface of road. Because of harm to road it influences the performance of vehicles and drivers. Solution for this issue is time taken and uneconomic. If defrosting and settlement happens for a long time and has ceased at certain time results into the development of the void cavity holes.
- In stratified soil deposits the distinct layers can have bearing stratum either softer or stiffer than the underneath stratum resulting in the generation of voids.
- In everyday life septic tanks in households and water sumps utilized for accumulation of drinking water are examples of formation of voids under or at some separation from footing of structures or different structures.

In actual, the depressions created after construction and usage of structure and are augmented ceaselessly on horizontal direction. In this manner voids formed after construction is not considered for the foundation framework design. The present study comprises of the determination of behavior of footing in terms of bearing capacity and settlement that are influenced by proximity of void. The investigation incorporates knowing the critical region under the footing influenced by void, considering diverse factors, for example, size of void, location of void and depth and proximity to the foundation.

CHAPTER -2

LITERATURE REVIEW

2.1 Introduction

Foundation is that part of the structure which transfers the loads to the soil or rock beneath it. Furthermore, it is characterized into two types specifically, (1) shallow foundation and (2) deep foundation by relying upon the depth of embedment. These foundations like earth retaining walls, oil/gas platforms and so on might be subjected to eccentric loads. This might be because of (i) wind load (ii) moments due to axial forces (iii) earth weight and water pressure. Pressure under the footing may not be uniform because of the eccentric loading, this causes the footing tilts and pressure changes underneath it. The tilt of footing is relative to the eccentricity. This implies that with enhancement in eccentricity, bearing capacity decreases consistently and experiences differential settlements.

2.2 Bearing capacity of foundation on granular soil

Stability of a structure for the most part relies on stability of bearing soil. For that the foundation must be stable against shear failure of the supporting soil and should not undergo settlement beyond a permissible limit to avoid harm to the structure. For a foundation to undergo its ideal capacity, one must ensure that it doesn't surpass its safe bearing capacity. The ultimate bearing capacity (q_u) is characterized as shear failure that happens in the supporting soil underneath the foundation.

Since the publications of Terzaghi's theory on the bearing capacity of shallow foundations in 1943, various studies (both theoretical and experimental) have been undertaken by various researchers. The greater part of these studies are related to footings subjected to vertical and central loads.

Meyerhof (1953) developed empirical methods for assessing the ultimate bearing capacity of foundations subjected to eccentric vertical loads. Researchers like Prakash and Saran (1971) and Purkayastha and Char (1977) considered the behavior of eccentrically loaded footings. A rigorous literature review has been done on bearing capacity of shallow strip foundations under various loading conditions are mentioned below.

2.2.1 Central Vertical Loading

Terzaghi (1943) recommended that the ultimate bearing capacity of a strip foundation subjected to a centric vertical load resting over a homogenous soil can be communicated as

$$q_u = cN_c + qN_q + 0.5\gamma BN_\gamma$$

For granular soil the above relation can be rewritten as:

$$q_u = qN_q + 0.5\gamma BN_\gamma$$

Similarly, generalized equation for centrally vertical loaded foundation was proposed by Meyerhof (1951) and it is expressed as

$$q_u = cN_c s_c d_c + qN_q s_q d_q + 0.5\gamma BN_\gamma s_\gamma d_\gamma$$

For granular soil, the above equation can further be reduced to the form:

$$q_u = qN_q s_q d_q + 0.5\gamma BN_\gamma s_\gamma d_\gamma$$

Where q_u = ultimate bearing capacity; q = surcharge pressure at the level of footing (γD_f); γ = unit weight of soil; D_f = depth of foundation; N_c, N_q, N_γ = bearing capacity factors; s_c, s_q, s_γ = shape factors; d_c, d_q, d_γ = depth factors;

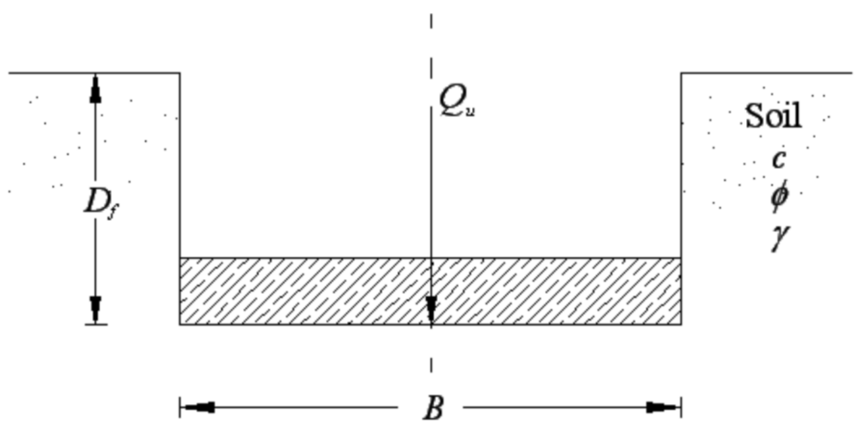

Figure 2.1: Vertical central load on the strip foundation for unit length (Q_u)

2.2.2 Eccentric vertical condition

Meyerhof (1953) presented an effective width (*B'*) method for eccentrically loaded foundations. The ultimate bearing capacity as per Meyerhof (1953) can be referred as

$$q_u = cN_{cq} + 0.5\gamma B' N_{\gamma q}$$

B'= effective depth = B – 2e; γ = density of soil; c = unit cohesion; N_{cq}, $N_{\gamma q}$ = resultant bearing capacity factors for a centric load and they depend on ϕ and *D/B'*

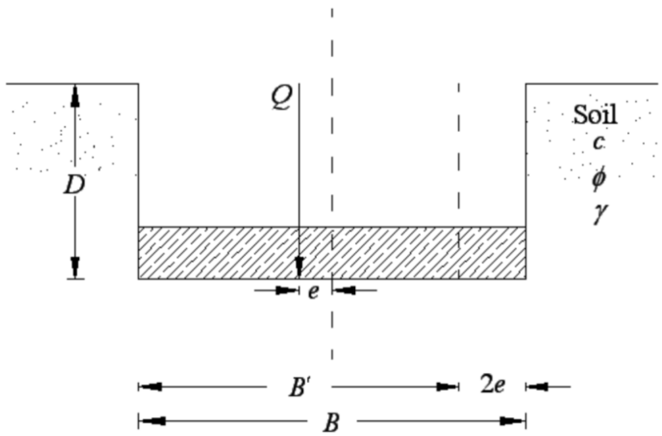

Figure 2.2: Eccentrically loaded shallow strip footing

Prakash and Saran (1971) proposed a concise and comprehensive mathematical relation to estimate the ultimate bearing capacity of a c–ϕ soil of rough strip foundation under eccentric load is as follows

$$q = cN_{c(e)} + \gamma D_f N_{q(e)} + \frac{1}{2}\gamma B N_{\gamma(e)}$$

where $N_{c(e)}$, $N_{q(e)}$, $N_{\gamma(e)}$ are the bearing capacity factors, functions of *e/B*, ϕ and foundation contact factor *x1*.

Michalowski and You (1998) proposed the bearing capacity of eccentrically loaded footings making use of the kinematic approach in limit analysis method. To find the bearing capacity of strip footing, charts are provided between bearing pressure and *e/B*.

2.2.3 Voids underneath the footing

The impact of void on the bearing capacity of foundation has been considered in many researches over the time and it plays a considerably significant role in foundation designing problems. Various methods, for example, Analytical, Experimental and numerical studies have been undertaken to know the behavior of footing because of the proximity of void. Some of studies are discussed below.

Badie et.al. (1984) examined stability of spread footing over continuous voids. The model footing tests were performed on kaolinite by considering circular voids for spread and circular footing and results were compared with theoretical outcomes utilizing three dimensional finite element program. The bearing capacity and settlement of footing with void for various cases and without void were analyzed and compared. In this study the depth of footing has been additionally considered and inferred that stability of footing can be essentially influenced when the void is situated inside the critical region under the footing.

Thomas and Billy (1987) built up a mathematical model to outline the road embankments with geosynthetics over voids and presented comparison results by performing different field tests to confirm the developed model. Computer investigation was conducted in light of the fact that the mathematical model includes an iterative analysis solution. The study inferred that geosynthetics can be utilized over voids of 3 m width.

Wang et.al. (1987) built up a rational model technique for stability of footing, complex conditions relating the most extreme footing pressure and other influencing parameters, for example, void size, location of void and soil stiffness and strength property. In this study upper bound limit analysis have been utilized to create conditional equations for strip footing with continuous void located centrally beneath footing. From previous analysis failure mechanisms of foundation soil have been considered for developing equations for failure footing pressure.

Azam et al. (1991) explored the behavior of strip footing over void supported by a homogeneous soil of finite thickness and a stratified deposit containing two layers. The study was conducted by method of two dimensional finite element analysis by considering round and rectangular voids with various cases and inferred that the footing behavior was influenced when depth to bed rock is six times the width of footing in the case of homogeneous soil and stiffness proportion of two layers, top layer thickness if there should be an occurrence of stratified soil deposits.

Kiyosumi et al. (2007) developed a calculation formula for assessing the yielding pressure of strip footing above various voids numerically utilizing two dimensional plane strain finite element method. This paper concentrates on the closest void which influences the behavior of footing than other voids. Sand cushioning over clay with void, the failure of soil was observed like punching shear failure. With depth increment of foundation, the thickness of soil layer over the void enhanced the results in increasing the bearing capacity because of soil arching effect. The affecting variables on bearing pressure and settlement of footing are relative density of sand fill, depth of geocell layer, base geogrid layer and width of geocell layer. The author inferred that with the increment in above variables the bearing capacity increased substantially.

Kiyosumi et al. (2011) have conducted a progression of loading test on shallow foundation of sedimentary rock considering square and rectangular voids. Failure mechanism were found relying on whether the void is located precisely beneath the center point of footing or at an eccentricity from center to footing. The bearing capacity of footing with void was discovered for various cases, for example, by changing the size of void, location, depth and proximity of voids both in horizontal and vertical direction were analyzed.

Sabouni (2013) inspected the impact of single and double voids on the settlement and effective stresses underneath the strip footing numerically through parametric study. A study was completed on size of void and location of void beneath the base. In this paper rectangular void has been considered with the various voids found both in horizontal and vertical direction. The settlement and bearing capacities are exhibited as percentage of no void condition.

Lee et al. (2014) explored the undrained vertical bearing capacity of strip footing on clay with single and double voids. The undrained bearing capacity factors were resolved utilizing design charts by method of finite element analysis.

2.2 Objective

To study the effect of flexible void on the ultimate bearing capacity of eccentrically loaded shallow strip footing on granular soil by varying location of void (*L/D*), diameter of void (*D/L*), horizontal location of voids (*H/B*) along the direction of eccentricity.

2.3 Thesis layout

The overview of the analysis and results on the above discussed aspects are mentioned in subsequent chapters as described below.

In Chapter 3, the methodology and modeling of test has been focused.

In Chapter 4, the results of the tests have been discussed where the impact of voids on the bearing capacity of footing with eccentric loading is considered in the dense type of sand along with the regression analysis and predictive modelling has been utilized for the equation formation.

In Chapter 5 brings the overall conclusions drawn from the mentioned chapters and suggestions for future research work.

CHAPTER - 3

METHODOLOGY AND MODELLING

3.1 Introduction

Foundation designing problems can be solved by two distinct methodologies: experimentally, by pursuing model and full-scale tests; or, analytically, by utilizing methods, like, finite element method. Full-scale tests are the perfect method for getting information, however, field practical challenges and financial constraints either wipe out or extensively confine the possibility of full-scale testing. As an alternative, model tests might be utilized, but they have various cons. The outcomes of these model tests are typically influenced by the limiting boundary conditions of the testing box, the dimensions of the footing, disturbance caused to the sample, the test setup and procedure of conducting the test. Due to the recent advancements in numerical analysis methods and numerical programming, it is beneficial to utilize these procedures to simulate the conditions of model test in order to affiliate the available theoretical approaches. The theoretical study can then be further extended out to cover an extensive variety of field problems which engineers excluded utilizing rigorous full-scale testing. In the present study, Numerical analysis will be performed by utilizing the software package “Plaxis 3D". It is finite element based program. The stresses, strains and disappointment parts of a given issue can be assessed by utilizing this product.

3.2 Methodology

The finite element program Plaxis3D (2013), was utilized to model the tests of strip footing on granular sand. Plaxis is supposed to be used for the deformation analysis and stability in geotechnical projects. The Mohr–Coulomb model was utilized for soil and Linear Elastic model was utilized for the footing; undrained trait is considered for the analysis and 10-node tetrahedral elements were utilized for the analysis. The test model of sand with strip footing having a void beneath the foundation at various different location (vertically downwards and horizontally along the direction of the eccentricity) and also the diameter of the voids is one of the considered parameter.

The parameters used in the analysis are tabulated below in the Table 3.1 and Table 3.2

Table 3.1: Soil properties

Sand type	**Unit weight, γ (kN/m^3)**	**Relative density of sand, D_r (%)**	**Elasticity modulus, E (kN/m^2)**	**Poisson's ratio ,ν**	**Friction angle, ϕ (°)**	**Dilatancy angle, ψ (°)**	**Cohesion, c (kN/m^2)**
Dense	14.37	72	42000	0.33	43	13	0

Table 3.2: Footing properties

Property	**units**	**Mild Steel plate**
Unit weight (γ)	kN/m^3	78
Young's modulus (E)	kN/m^2	$2*10^8$
Poisson's ratio (ν)		0.3

3.2.1 Modelling

Initially, soil model of dimension 1.6 m x 0.5 m x 0.655 m is created and a footing of dimension 0.1 m x 0.5 m x 0.03 m is placed on the top surface of the soil model centrally. The soil model is introduced with a void of specific dimension and at various different location depending on the variating parameter considered. It is the hollow cavity introduced in the model by deactivating the surface created volume (or hollow space). A fine mesh is generated for the model geometry simulated. A staged surface incremental loading is applied at the center of the footing. A point i.e. at the center and top of the soil model and at the bottom of the footing is selected for the analysis and then analysis is done up to the instant when the soil body collapses or the failure occurs in the soil. After getting the results, the plot used to be drawn from the analysis done and a load - settlement curve is drawn and ultimate bearing capacity of the strip footing is found out at that particular failure load. Same methodology has been adopted for various loading conditions and by changing the different parameters to obtain the ultimate bearing capacity of the strip footing at that particular loading condition

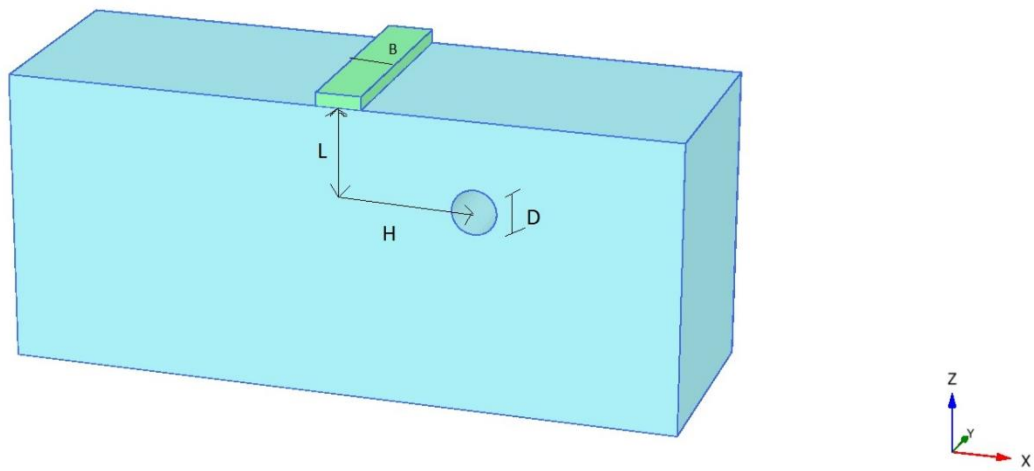

Figure 3.1 Geometric model for footing with a void

In the 3D geometrical model of footing with the void shown in Figure 3.1, various different parameters are marked which have specific meanings as mentioned below.

Where,

L = Location of the void center from the bottom of the footing; *H* = Horizontal distance between the footing center to the void center along the direction of the eccentricity provided; *D* = Diameter of the void; *B* = Width of the footing

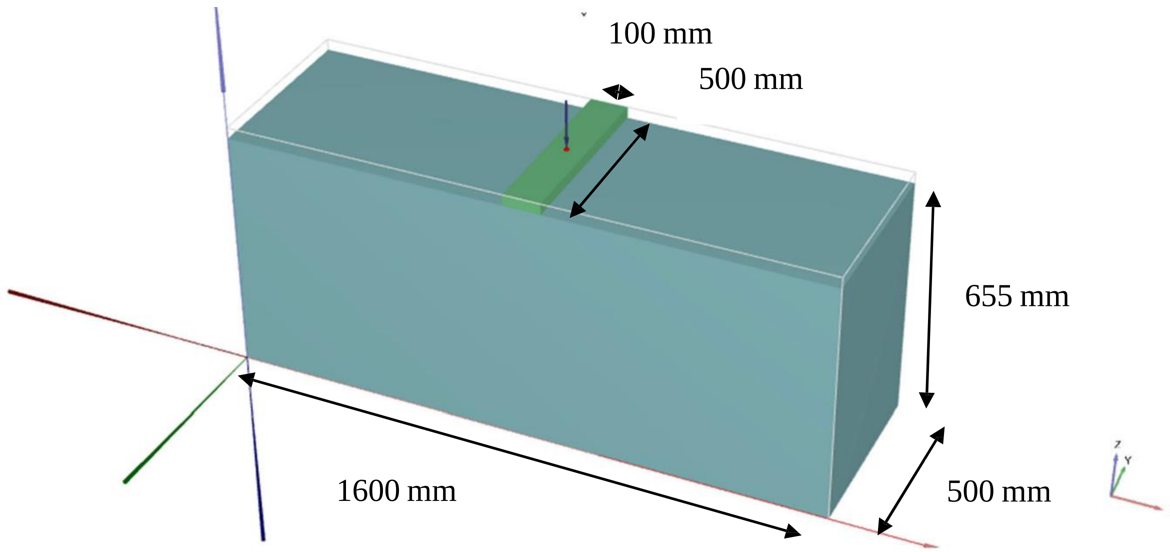

Figure 3.2: Geometric model for central vertical loading case

CHAPTER – 4

EFFECT OF FLEXIBLE VOID ON ULTIMATE BEARING CAPACITY OF STRIP FOOTING SUBJECTED TO ECCENTRIC VERTICAL LOAD

4.1 Introduction

Meyerhof (1953) has suggested a semi empirical procedure to determine the ultimate bearing capacity of shallow foundations due to eccentric loading condition. Eccentric loading of shallow foundations occurs when a vertical load Q is applied at a location other than the centroid of the foundation. To determine the extent of impact on the bearing capacity of soil various tests model has been simulated numerically with the strip footing subjected to eccentric vertical load resting on granular dense sand and their results are being compared with the Meyerhof's empirical equation. Based on the analysis of numerical models result, the numerical models result have been compared with developed non-dimensional reduction factor of Patra et al. (2012a), which has been used for estimating the ultimate bearing capacity.

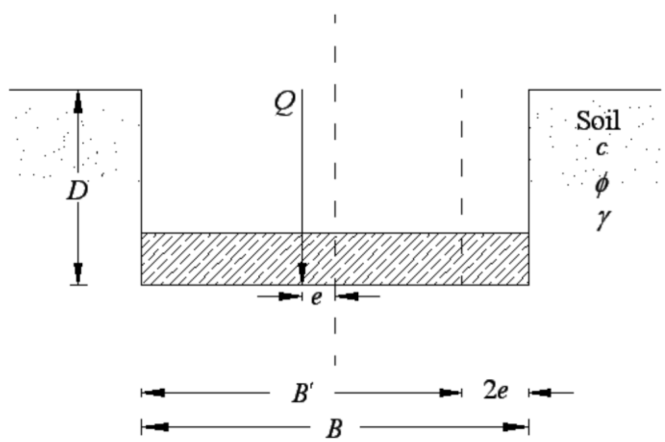

Figure 4.1: Eccentrically loaded strip footing

4.2 Numerical analytical module

Twelve models have been generated and analyzed numerically by varying the different eccentricity ratio, e / *B* (i.e. 0, 0.05, 0.1 and 0.15) along with the variation in the embedment depth ratio D_f / *B* (i.e.0, 0.5 and 1)

4.3. Model tests

Twelve numerical models have been developed for the centric vertical loading condition with strip footing. The details of the parameters varied in the models are tabulated below:

Table 4.1: Range of eccentricity and embedment depth ratio varied

D_f/B	*e/B*
0	0
0.5	0.05
1	0.1
	0.15

4.3.1 Model Analysis

Twelve number of numerical models are established in central vertical condition (i.e. *e*/*B* =0). The details of the model parameters are shown in Table 4.2. In general , there are five different methods to predict the ultimate bearing capacity from the load-settlement curve namely , Log- Log method (DeBeer 1970), Tangent Intersection method (Trautmann and Kulhawy 1988), 0.1*B* method (Briaud and Jeanjean 1994), Hyperbolic method (Cerato 2005), and Break Point method (Mosallanezhad et al. 2008), the ultimate bearing capacity is determined by Break Point method [Figure 4.2] for the present test results, as after the point of "failure load" with small increase in load there happens significant increase in settlement.

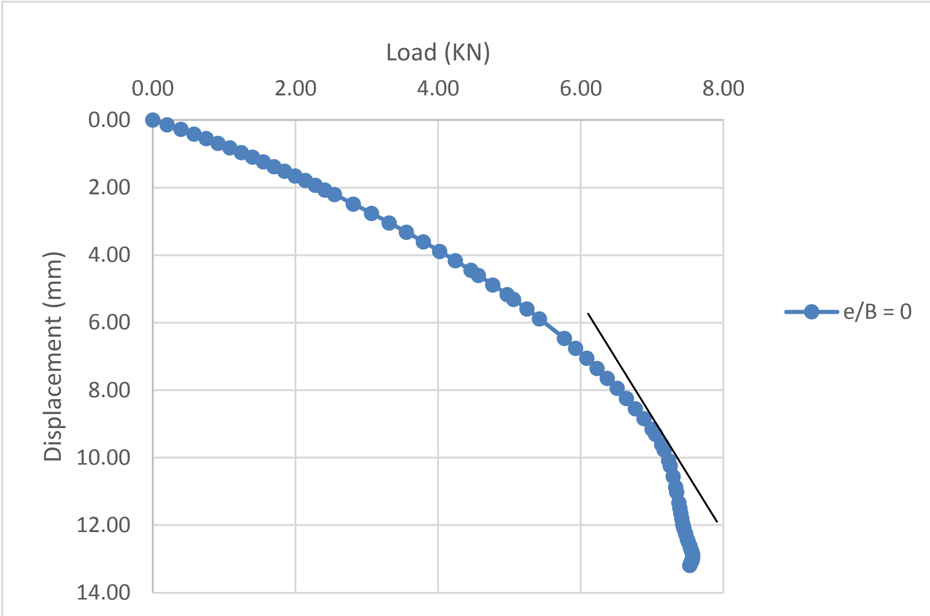

Figure 4.2: Interpretation of Ultimate bearing capacity q_u by Break Point method (Mosallanezhad et al. 2008)

4.3.2 Model Test Parameters

For analyzing the ultimate bearing capacity of the strip footing subjected to centric vertical load resting on dense granular sand, various strength and stiffness parameters have been considered in the numerical analysis of the model using the PLAXIS software package module. The parameters considered has been tabulated below:

Table 4.2: Numerical model parameters for Centric Vertical Loading condition

Sand type	**Unit weight, γ**	**Relative density of sand**	**Elasticity modulus,**	**Poisson's ratio , ν**	**Friction angle, ϕ**	**Dilatancy angle, ψ**	**D_f/B**	**e/B**
Dense	14.37	72	42000	0.33	43	13	0	0
							0.5	
							1	

The bearing capacity of the footing increases with the increase in the embedment depth (i.e. D_f/B) ratio. The increment in the bearing capacity with the embedment depth can be easily inferred from the graph in the Figure 4.3.

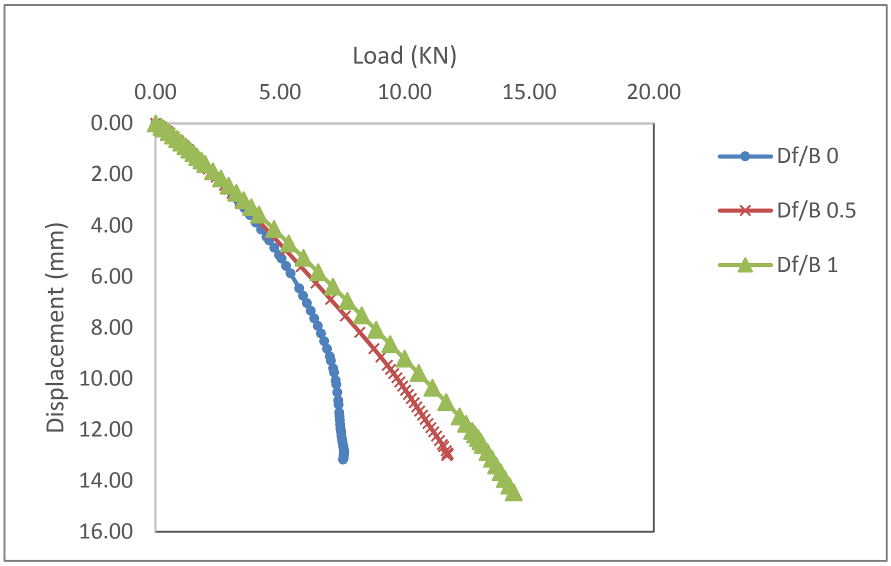

Figure 4.3: Variation of load-settlement curve with embedment ratio (D_f/B) at e/B=0 in dense sand

The ultimate bearing capacities for centric vertical loading (e/B = 0) at D_f/B = 0, 0.5 and 1.0 for dense sand are obtained using the expression of Meyerhof and other recently developed theories like that of Patra et al (2012). The values are plotted in Fig. 4.4 and are also presented in the Table 4.3. It can be seen that model tests bearing capacities for a given D_f/B are significantly in proximity to the existing theories. Unlike experimental results, there is no scale effect associated with the model tests.

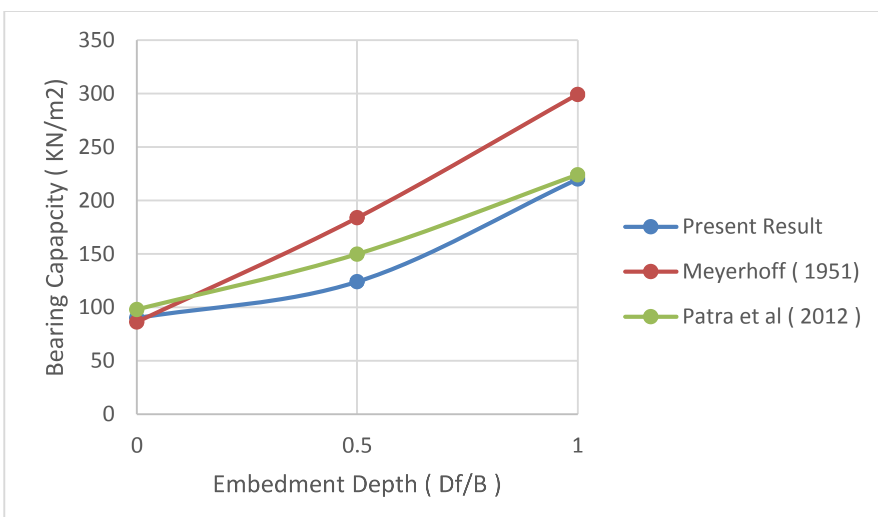

Figure 4.4: Variation of q_u with D_f/B for e/B = 0.15 using formulae of existing theories along with present model test values for dense sand

Table 4.3: Calculated values of ultimate bearing capacities q_u by Meyerhof (1951), Patra et al. (2012) for centric vertical condition along with Present results

e/B	***D_f/B***	**Meyerhof(1951) q_u (kN/m²)**	**Patra et al. (2012); q_u(kN/m²)**	**Present result; q_u(kN/m²)**
		ϕ=43°	**ϕ=43°**	**ϕ=43°**
0.15	0	86.25	98	90
0.15	0.5	183.7	149.8	124
0.15	1	299.21	224	220

With the graph in the Figure 4.4 and Table 4.3, it can be inferred clearly that, at zero embedment depth all the results i.e. from already existing theories of Meyerhof (1953) and Patra et al. (2012) comes in great concordance to the bearing capacity obtained from the numerical analysis done by PLAXIS. Moreover, for higher embedment depth, this trends don't follow. The bearing capacity obtained using Patra et al. comes in great proximity to the calculated values but the Meyerhof theory predicted bearing capacity values are having great variation from the calculated ones. The trend shown by the Meyerhof equation is quite obvious as it is the known fact, that Meyerhof equation does not comply well for the foundation with eccentric load as it over predicts the value.

The observed failure surface for footing resting on dense sand in centric vertical condition (i.e. D_f/B=0, e/B=0) is shown in Figure 4.5. Up to the depth of B the effect of load applied is considerable beyond that it decreases gradually and at a depth of 2B it almost nullifies.

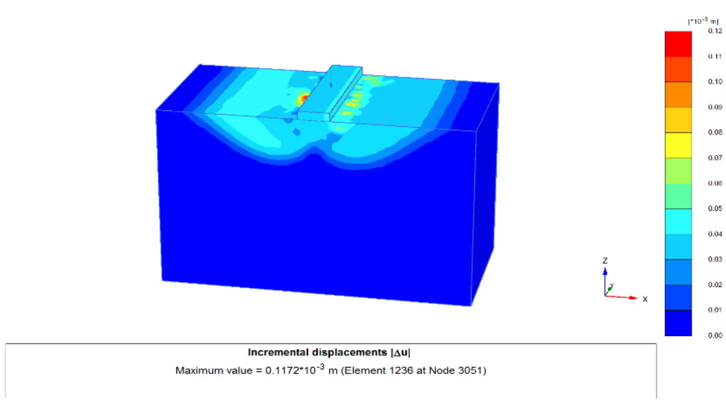

Figure 4.5: Failure surface observed in dense sand in surface condition at D_f/B = 0 and e/B = 0

4.4 Eccentric vertical loading conditions

Nine models tests are developed in eccentric vertical condition. The details of the numerical model parameters are shown in Table 4.4. The developed numerical model for one case of eccentric vertical loading condition is as shown in Figure 4.6. The load settlement curves of strip foundations (e/B=0, 0.05, 0.1 and 0.15) on dense sand in surface condition are plotted in Figure 4.7. The load carrying capacity decreases gradually with increase in the e/B ratio. Similarly, Figures 4.8 shows the variation of load-settlement curve with depth of embedment (D_f/B).

Table 4.4: Model test parameters for Eccentric Vertical Loading condition

Sand type	**Unit weight, γ (kN/m³)**	**Relative density of sand Dr (%)**	**Friction angle, ϕ (°)**	**D_f/B**	**e/B**
Dense	14.37	72	43	0 0.5 1	0 0.05 0.1 0.15

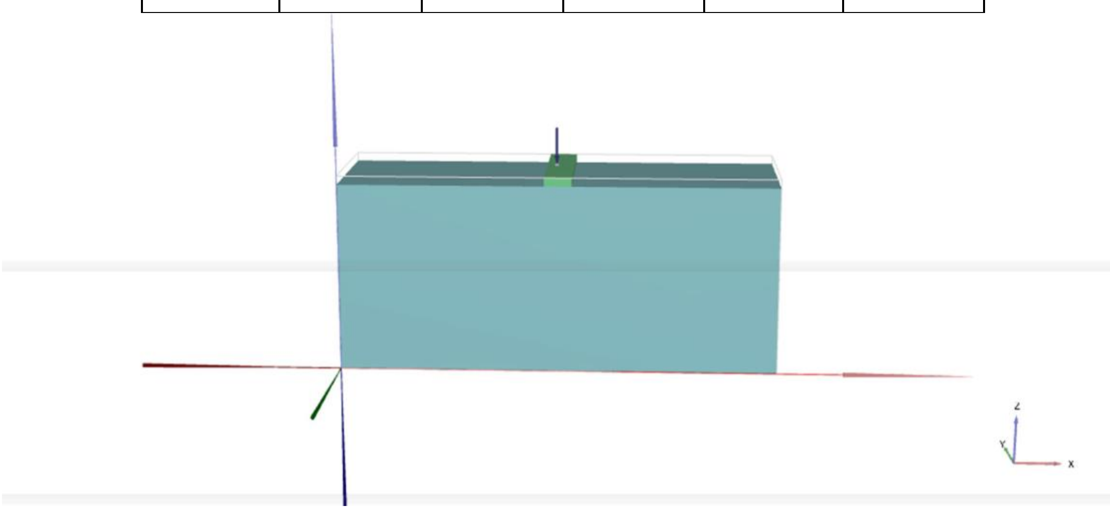

Figure 4.6: Developed numerical model for eccentric vertical loading condition

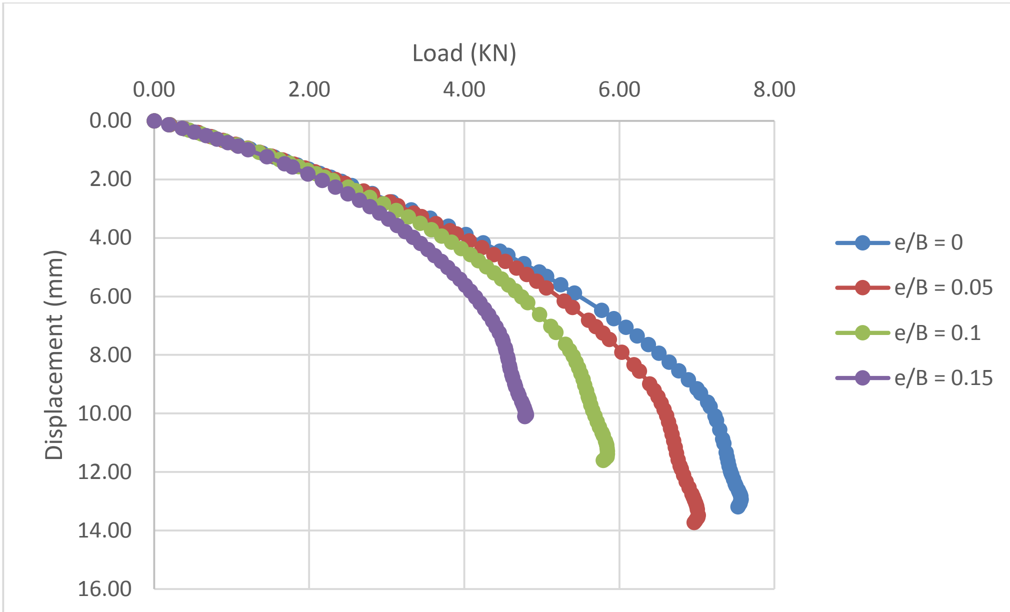

Figure 4.7: Variation of load settlement curve with eccentric load in dense sand for surface condition

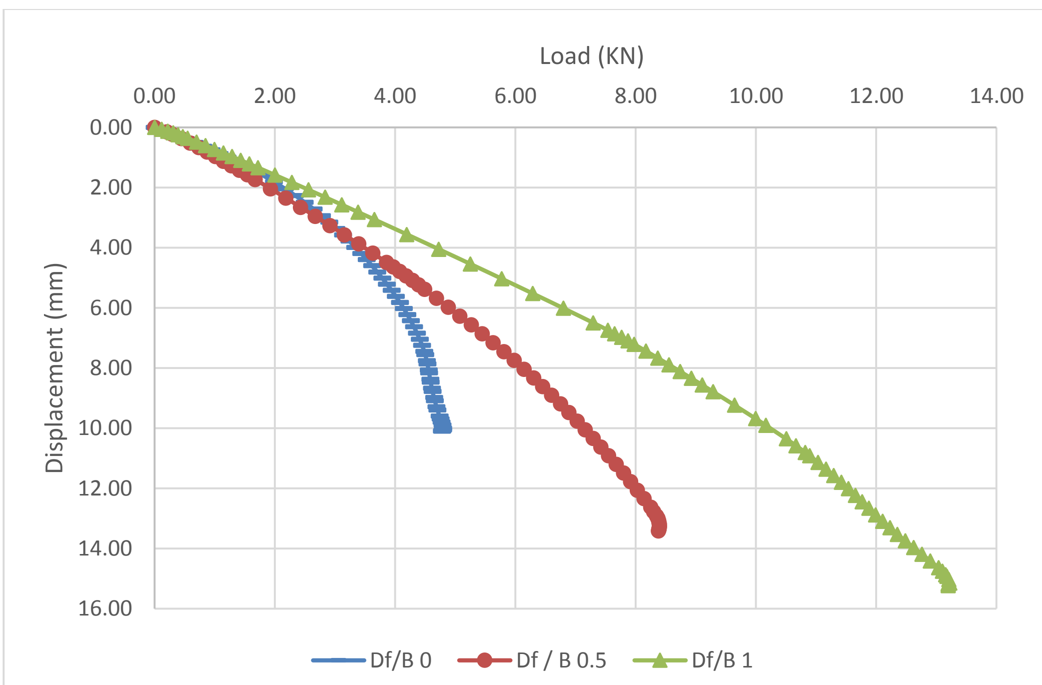

Figure 4.8: Effect of embedment on eccentricity in Dense sand for e/B=0.15

The numerical models ultimate bearing capacities for eccentrically loaded foundations (e/B=0, 0.05, 0.1 and 0.15, D_f/B = 0, 0.5 and 1, and D_r = 72%) are plotted along with the bearing capacities obtained by using existing theories. The results are shown in Figure 4.9 and Table 4.5.

The nature of decrease of bearing capacity with the increase in eccentricity as observed from numerical models results are in good accordance with the existing theories. The observed failure surface for footing resting on dense sand in eccentric vertical condition (i.e. D_f/B=0, e/B=0.1) is shown in Figure 4.10.

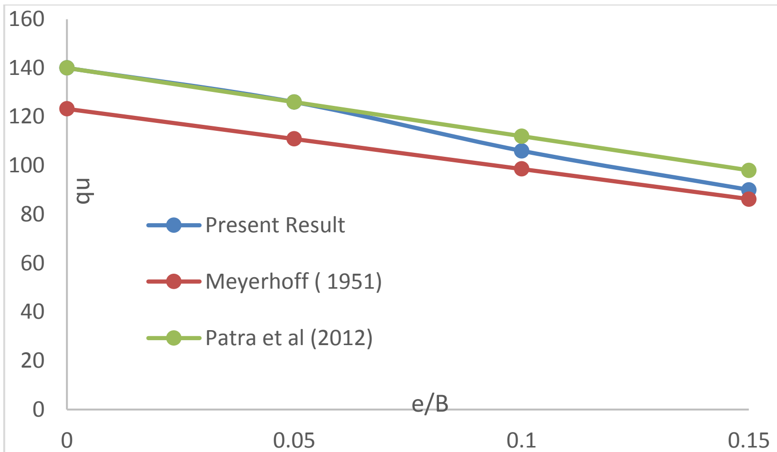

Figure 4.9: Comparison of ultimate bearing capacities of Present results with existing theories in dense sand for D_f/B = 0 at different e/B

Table 4.5: Calculated values of ultimate bearing capacities q_u by Meyerhof (1951), Patra et al. (2012) for centric vertical condition along with Present results

e/B	D_f/B	Meyerhof (1951); q_u	Patra et al. (2012); q_u	Present results; q_u
		ϕ= 43°	ϕ= 43°	ϕ= 43°
0	0	123.24	140	140
0.05	0	110.89	126	126
0.1	0	98.57	112	106
0.15	0	86.25	98	90
0	0.5	224.91	214	214
0.05	0.5	211.18	192.6	174
0.1	0.5	197.44	171.2	144
0.15	0.5	183.7	149.8	124
0	1	344.75	320	320
0.05	1	329.52	288	290
0.1	1	314.37	256	260
0.15	1	299.21	224	220

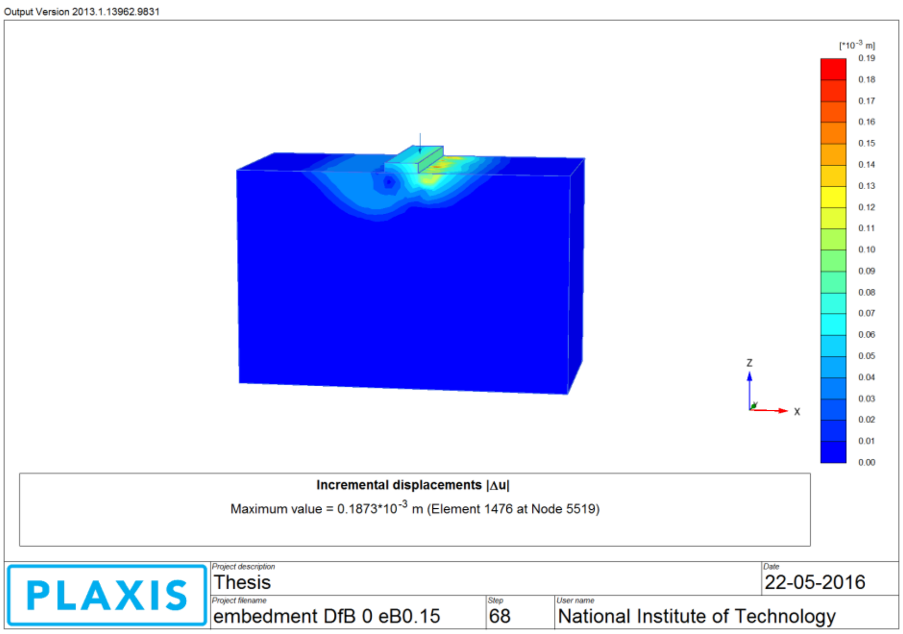

Figure 4.10: Failure surface observed in dense sand at $D_f/B = 0$, and $e/B = 0.15$

4.5 Structural instability due to flexible void

Voids happens under structures with adequate recurrence to warrant unique consideration, since voids may bring about extreme structural harm and death toll. Voids may happen as a consequence of mining, burrowing, or solution cavity in a dissolvable rock. Solution cavity may exist at any profundity in the solvent bedrock; there are occurrences in which solvent bedrock breaks up away at the soil-bedrock interface leaving the overburden soil connecting over the void. Mining operations have left innumerable number of underground voids. With populace development and the subsequent expansion of the urban sprawl to the territories of earlier mining action, there is developing worry to the geotechnical engineer in regards to foundation dependability. Comparable concern additionally emerges with respect to the stability of the foundations above delicate ground tunnels in view of the expanding interest of transportation passages in the urban and rural locations.

To address the problem of instability of the foundation caused due to the occurrence of the voids, various numerical test models have ben simulated in PLAXIS with different locations of the voids beneath the strip footing. The impact of voids on the ultimate bearing capacity has been studied numerically by changing the location of the void (i.e. *L/D* ratio), diameter of the voids (i.e. *D/L* ratio) and also by changing the void location in the horizontal direction (*H/B* ratio) i.e. in the direction of the shifting of the eccentricity. The void has been introduced in the model tank beneath the footing by changing its location, diameter and horizontal location as shown in the Figure. 4.11.

4.6 Numerical Module

One hundred and forty-four models have been developed under the condition of strip footing resting on the dense sand and the load is applied in the centric and eccentric footing resting on the dense sand and the load is applied in the centric and eccentric way. The parameters considered in the numerical models with the voids underneath the footing are Location of the voids (L/*D* = 0.5, 1, 1.5, 2 and 3), Diameter of the voids (D/*L* = 0.25, 0.5 and 0.75) and the horizontal location of the void (H/*B* = 0, 1, 2 and 3) with respect to the strip footing along the direction of the provided eccentricity (mentioned below in the Table 4.6).

Table 4.6. Parameters considered in the modelling

D_f / B	*e/B*	*L/D*	*D/L*	*H/B*	**Type of Sand**
0 0.5 1	0 0.05 0.1 0.15	1 1.5 2 3	0.25 0.5 0.75	0 1 2 3	Dense Sand (D_r =72%)

4.7 Model Test Results

4.7.1 Effect of Void Location on q_u

The location of the void beneath the strip footing i.e. *L/D* ratio has been changed from 0.5 to 3 keeping the diameter of the void to be constant at the value of 0.1 m. The void has

been shifted with respect to the strip footing vertically downwards. The *L/D* ratio has been restricted to three only as because on increasing the *L/D* further to four, there is no impact on the bearing capacity of the strip footing.

With the numerical results obtained by PLAXIS, it can be easily inferred that with increase in the depth of the void or with increase of the *L/D* ratio, the ultimate bearing capacity of the test setup increases for any specific combination of parameters. Moreover, Ultimate Bearing Capacity follows the same trend (no voids case) for the embedment depth and the eccentricity ratio but lesser in magnitude (due to the presence of the void) i.e. With the increase in the embedment depth, the ultimate bearing capacity of the footing increases and with the increase in the eccentricity ratio, the ultimate bearing capacity of the soil decreases. The trend of the ultimate bearing capacity at different eccentricities for the *L/D* = 2, *Df/B* = 0 is shown in Figure 4.12. The increase in the bearing capacity with the embedment depth for *L/D* = 1.5 and *e/B* 0.15 is shown in Figure 4.13. The increment in the bearing capacity with the increase in the depth of the void location (or increase in the *L/D* ratio) for *Df/B* =1 and *e/B* 0.15 is shown in Figure 4.14.

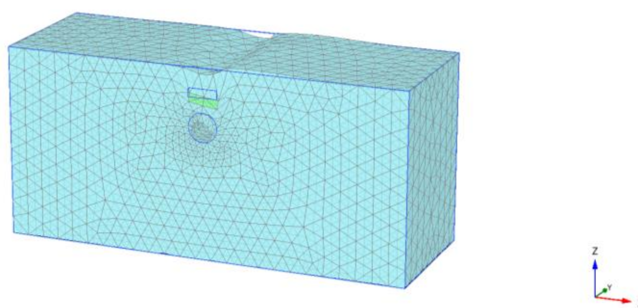

Figure 4.11 : Deformed Mesh size for footing with a void

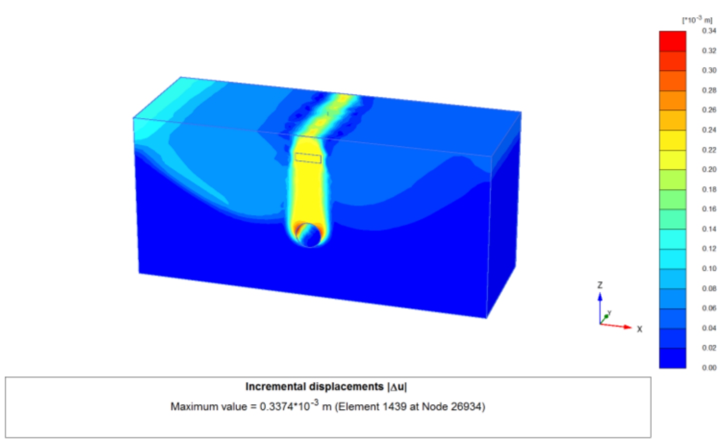

Figure 4.12: Failure envelope for the embedded footing with voids at L/D = 3

The Figure 4.11 shows the failure envelope of the strip footing with the embedment depth of D_f/B = 1, e/B =0 and the location of the void at L/D = 3.

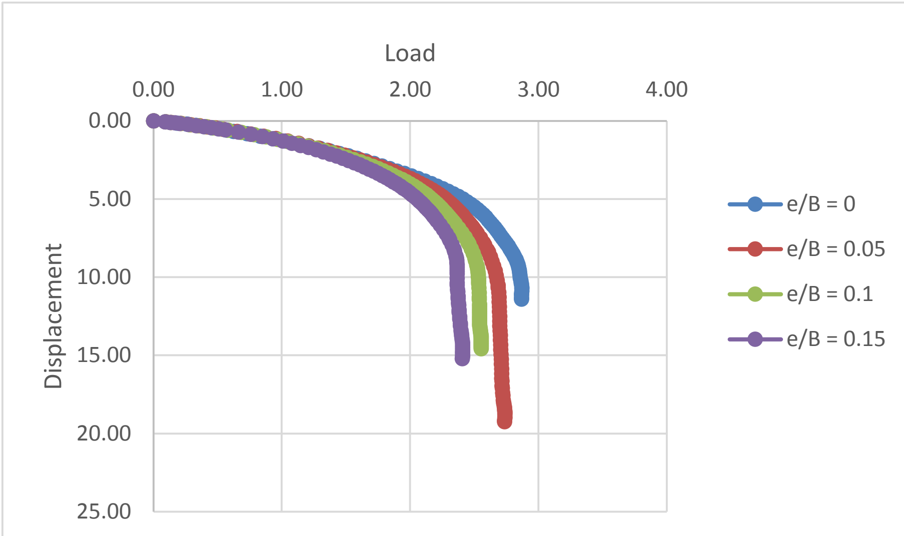

Figure 4.13 Variation of Load-Displacement for L/D = 2 and D_f/B = 0

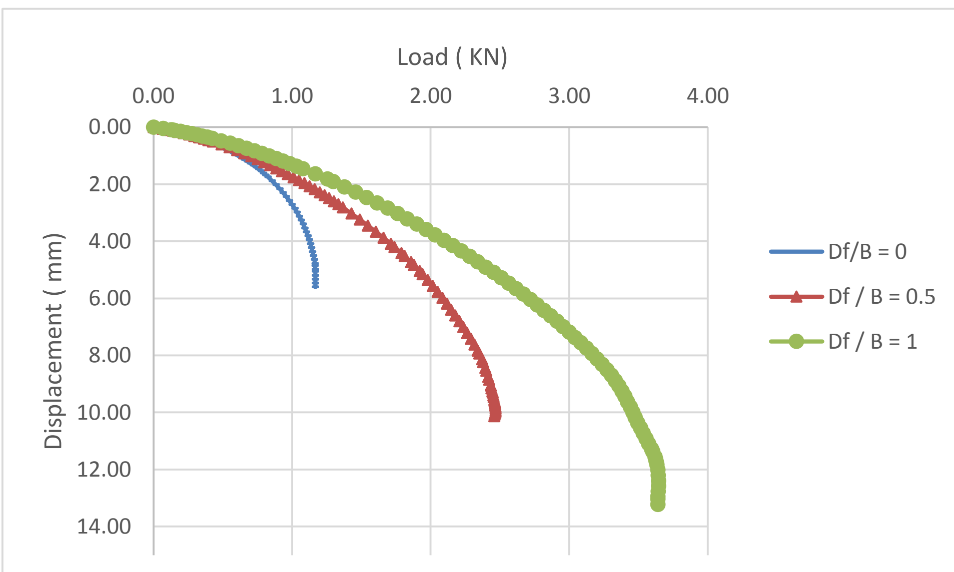

Figure 4.14 Variation of Load-Displacement for L/D = *1.5* and e/B = 0.15

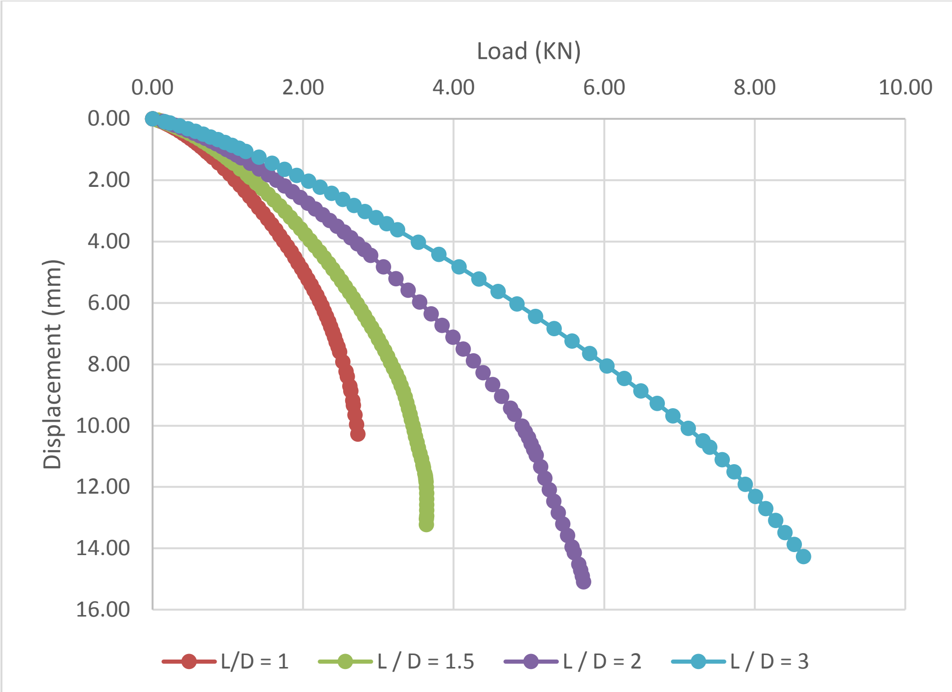

Figure 4.15 Variation of Load-Displacement for D_f / B = 1 and e/B = 0.15

The ultimate bearing capacity of the strip footing resting on the granular soil subjected to the eccentric load having a void underneath the footing has been calculated using PLAXIS and tabulated in Table 4.7. The ultimate bearing capacity has been obtained by varying the void location vertically downwards i.e. increasing the depth of the void below the footing by increasing the L/D ratio.

The location of the void has been varied from *L/D = 1* to *L/D = 4*. The effect of the void on the ultimate bearing capacity has been observed only up to the L/D ratio of three. The void location beyond the *L/D = 3* does not have any impact on the bearing capacity of the soil as in that case, the void goes beyond the region of influence of the footing loading on the soil.

Table 4.7: Ultimate Bearing Capacity of strip footing with various L/D Ratio.

L/D	**D_f/B**	***e/B***	**q_u (kN/m^2)**
1	0	0	13.2
1	0	0.05	11
1	0	0.1	9.8

L/D	***D_f/B***	***e/B***	***q_u* (kN/m²)**
1	0	0.15	8.8
1	0.5	0	36
1	0.5	0.05	34
1	0.5	0.1	31
1	0.5	0.15	29
1	1	0	49
1	1	0.05	46
1	1	0.1	43
1	1	0.15	38
1.5	0	0	30
1.5	0	0.05	27.6
1.5	0	0.1	25.4
1.5	0	0.15	23.6
1.5	0.5	0	55
1.5	0.5	0.05	52
1.5	0.5	0.1	50
1.5	0.5	0.15	48
1.5	1	0	80
1.5	1	0.05	77
1.5	1	0.1	72
1.5	1	0.15	68
2	0	0	56
2	0	0.05	52
2	0	0.1	49
2	0	0.15	46
2	0.5	0	86
2	0.5	0.05	82
2	0.5	0.1	76

L/D	***D_f/B***	***e/B***	**q_u (kN/m^2)**
2	0.5	0.15	72
2	1	0	125
2	1	0.05	120
2	1	0.1	110
2	1	0.15	100
3	0	0	112
3	0	0.05	105
3	0	0.1	100
3	0	0.15	92
3	0.5	0	147
3	0.5	0.05	140
3	0.5	0.1	130
3	0.5	0.15	120
3	1	0	200
3	1	0.05	190
3	1	0.1	178
3	1	0.15	170
4	**0**	**0**	**140**

From the data tabulated in Table 4.7, it can be clearly inferred that with the increase in the depth of the voids, the bearing capacity of the strip footing increases i.e. with increase in the L/D ratio the void goes farther from the footing and away from the zone of influence of the footing load and thus the impact of the voids on the decrement of the bearing capacity also decreases. The ultimate bearing capacity of the footing at *L/D* = 4, *Df/B* =0 and *e/B* = 0 is equals to 140 KN/m^2, which is similar to the case of no voids with *Df/B* =0 and *e/B* =0. Thus, voids do have the impact on the bearing capacity only up to the extent of *L/D* = 3.

4.7.2 Effect of Diameter of Voids on q_u

The diameter of the voids is varied by changing the *D/L* ratio to 0.25, 0.5 and 0.75. The case of *D*/L = 0.5 is the median case. The void with the *D/L* ratio as 0.25 reduces the void dimension and gives the increment in the ultimate bearing capacity, whereas the *D/L* ratio of 0.75 increases the void diameter and thus reduces the bearing capacity. The variation of the Load – Displacement curve with different eccentricities having embedment depth D_f/B = 0 and *D/L* = 0.5 is shown in Figure 4.15 and the variation of Load – Displacement curve having the *e/B* = 0.15 and *D/L* = 0.75, keeping the embedment depth as the variate is shown in Figure 4.16. Thus, with the Figure 4.17 (where D_f/B =1 and *e/B* = 0) and the Table 4.8, it can be inferred that with the increase in the diameter of the void beneath the footing, the bearing capacity of the soil decreases keeping the location of the void as constant.

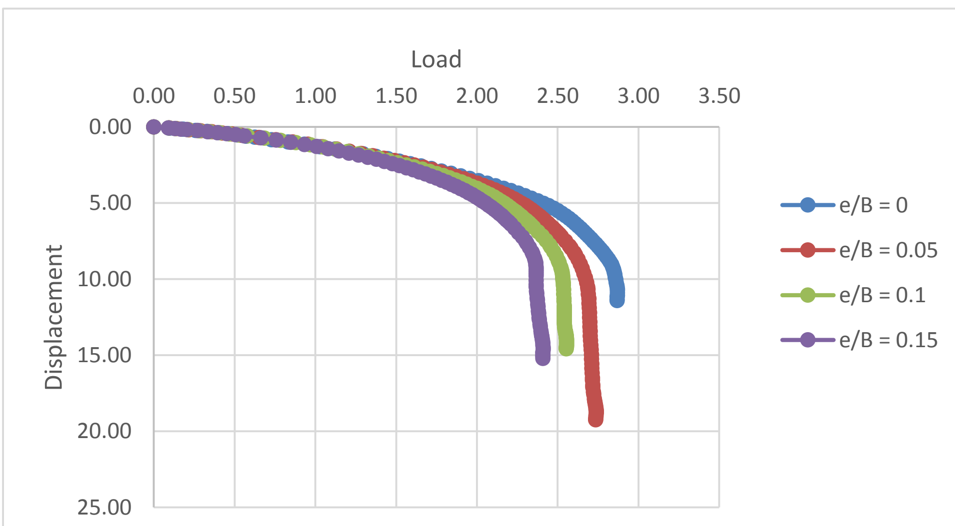

Figure 4.16 Variation of Load – Displacement for *D/L* = 0.5 and D_f/B = 0

For the same embedment depth and *D/L* ratio, the bearing capacity of the soil decreases with the increase in the eccentricity ratio from 0 to 0.15.

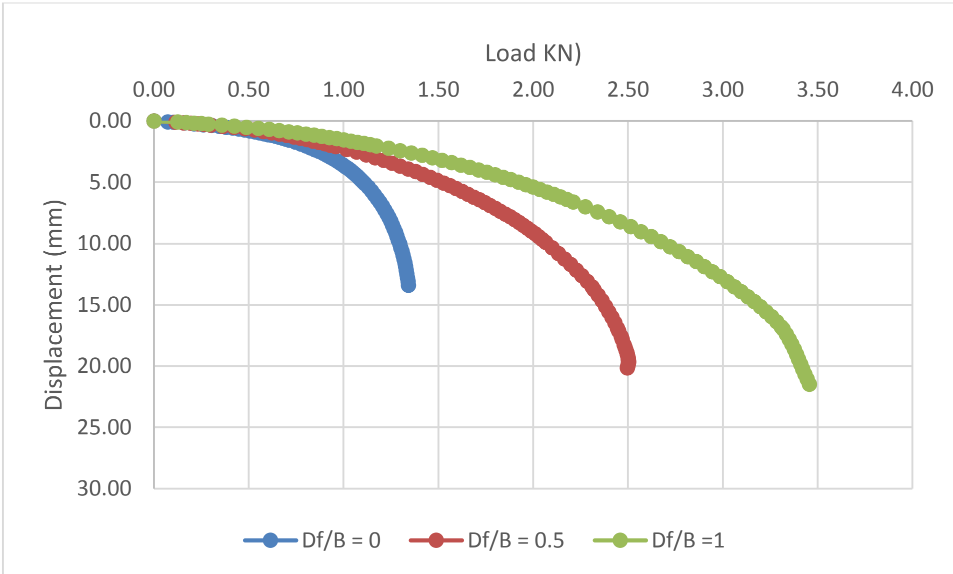

Figure 4.17 Variation of Load – Displacement for *D/L* = 0.75 and *e/B* = 0.15

With increase in the embedment depth of the strip footing (keeping the *D/L* ratio and the *e/B* ratio as the constant), the ultimate bearing capacity of the footing also increases.

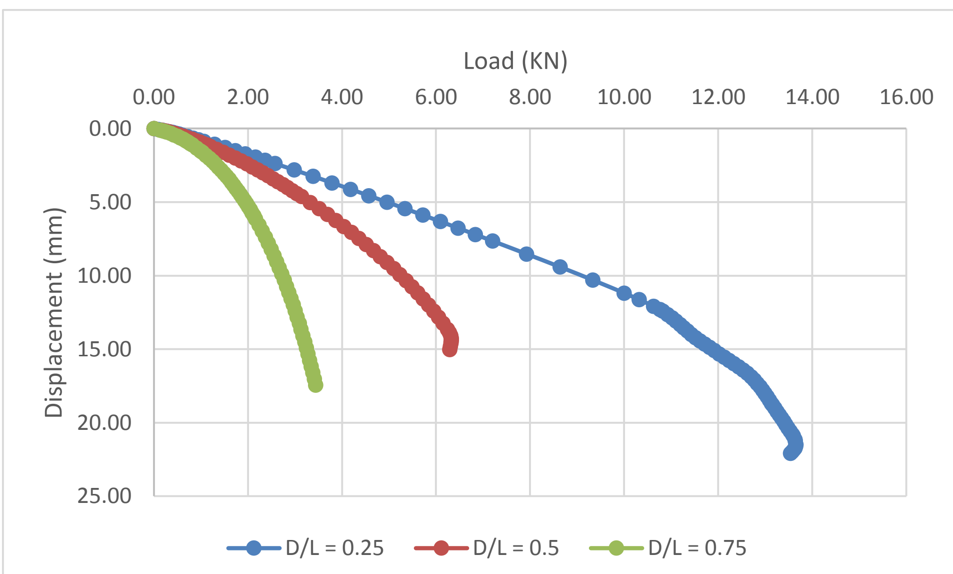

Figure 4.18 Variation of Load – Displacement for *Df/B* =1 and *e/B* = 0

Table 4.8: Ultimate Bearing Capacity of strip footing with various *D/L* Ratio.

D/L	***D_f/B***	***e/B***	**q_u (kN/m^2)**
0.25	0	0	130
0.25	0	0.05	120
0.25	0	0.1	100
0.25	0	0.15	89
0.25	0.5	0	140
0.25	0.5	0.05	130
0.25	0.5	0.1	122
0.25	0.5	0.15	110
0.25	1	0	220
0.25	1	0.05	200
0.25	1	0.1	180
0.25	1	0.15	158
0.5	0	0	56
0.5	0	0.05	52
0.5	0	0.1	49
0.5	0	0.15	46
0.5	0.5	0	86
0.5	0.5	0.05	82
0.5	0.5	0.1	76
0.5	0.5	0.15	72
0.5	1	0	125
0.5	1	0.05	120
0.5	1	0.1	110
0.5	1	0.15	100
0.75	0	0	29
0.75	0	0.05	28

D/L	***D$_f$/B***	***e/B***	**q_u (kN/m^2)**
0.75	0	0.1	27.4
0.75	0	0.15	26
0.75	0.5	0	53
0.75	0.5	0.05	52
0.75	0.5	0.1	50.8
0.75	0.5	0.15	49
0.75	1	0	74
0.75	1	0.05	72
0.75	1	0.1	69.6
0.75	1	0.15	66.4

The model in Figure 4.18 shows the failure envelope of the surface strip footing resting on the granular soil for *D/L* as 0.25

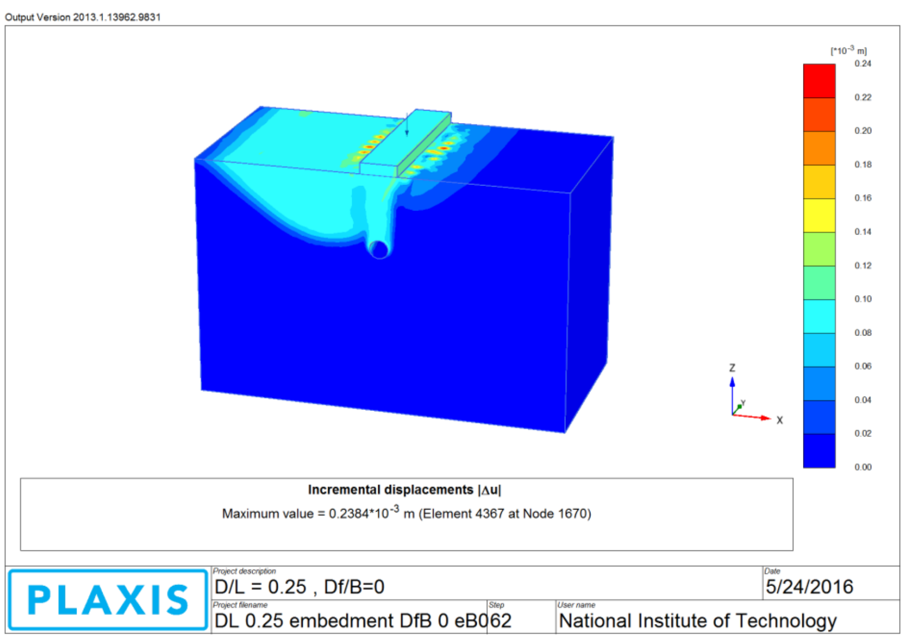

Figure 4.19: Failure envelope for the surface footing of voids with *D/L* = 0.25

4.7.3 Effect of *H/B* on q_u

The location of the void has been variated in the horizontal direction along the provided eccentricity by variating the *H/B* ratio (*H/B* = 0, 1, 2 and 3). With the increase in the value of the *H/B* ratio from 0 to 3, the void shifted in the direction of the eccentricity variation. The variation of the Load – Displacement curve with different eccentricities having embedment depth *Df/B* = 0 and *H/B* = 2 is shown in Figure 4.19 and the variation of Load – Displacement curve having the *e/B* = 0.15 and *H/B* = 3, keeping the embedment depth as the variate is shown in Figure 4.20. The variation in the ultimate bearing capacity due to the different *H/B* ratio is tabulated in the Table 4.9.

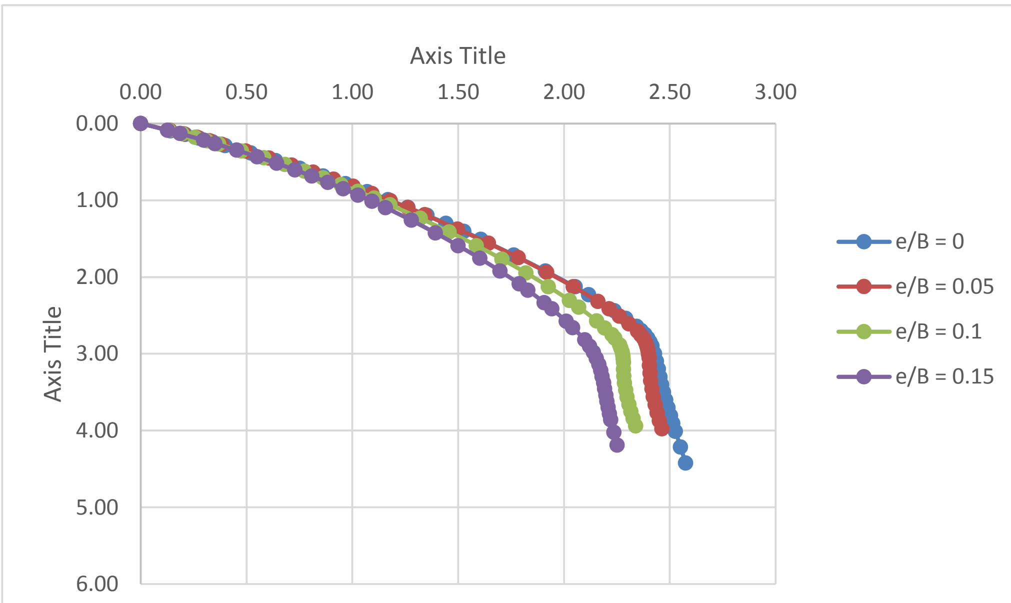

Figure 4.20 Variation of Load – Displacement for *H/B* = 2 and D_f/B = 0

The trend is clear from the plot that with the increase in the eccentricity ratio, the ultimate bearing capacity of the model tests decreases gradually.

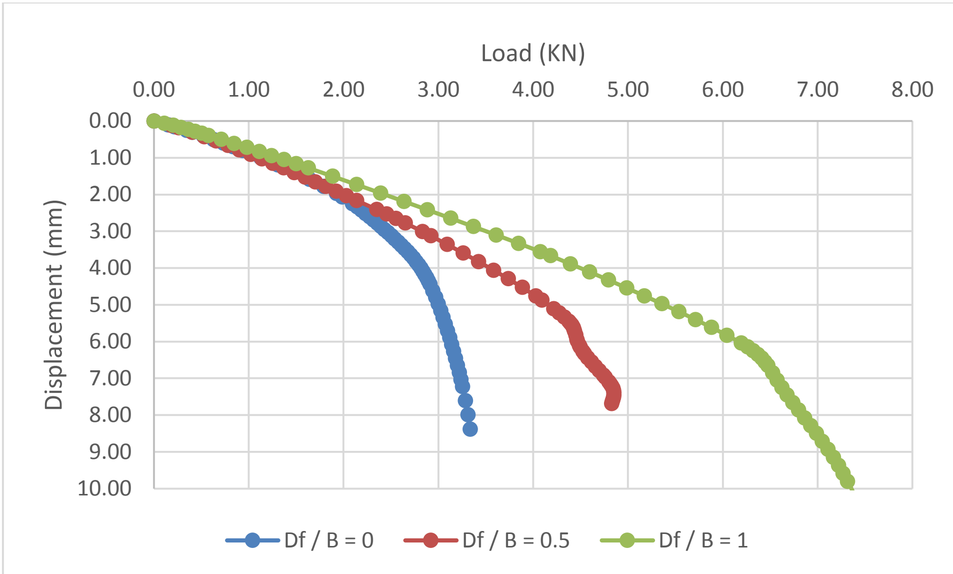

Figure 4.21 Variation of Load – Displacement for *H/B* = 3 and *e/B* = 0.15

It can be inferred from the plot that with the increase in the embedment depth of the footing in the soil, the ultimate bearing capacity of the footing increases in accordance with it.

Table 4.9: Ultimate Bearing Capacity of strip footing with various *H/B* Ratio.

H/B	***D_f/B***	***e/B***	**q_u (kN/m^2)**
0	0	0	56
0	0	0.05	52
0	0	0.1	49
0	0	0.15	46
0	0.5	0	86
0	0.5	0.05	82
0	0.5	0.1	76
0	0.5	0.15	72
0	1	0	125
0	1	0.05	120

H/B	***D**f**/B***	***e/B***	***q_u* (kN/m^2)**
0	1	0.1	110
0	1	0.15	100
1	0	0	65
1	0	0.05	64
1	0	0.1	62.8
1	0	0.15	61.8
1	0.5	0	71
1	0.5	0.05	69
1	0.5	0.1	67
1	0.5	0.15	65
1	1	0	108
1	1	0.05	106
1	1	0.1	102
1	1	0.15	97
2	0	0	49
2	0	0.05	47
2	0	0.1	44
2	0	0.15	42
2	0.5	0	82.4
2	0.5	0.05	81
2	0.5	0.1	78
2	0.5	0.15	74
2	1	0	129
2	1	0.05	122
2	1	0.1	117
2	1	0.15	110
3	0	0	70
3	0	0.05	67

H/B	*D*D_f/B	*e/B*	q_u (kN/m^2)
3	0	0.1	63.4
3	0	0.15	60
3	0.5	0	106
3	0.5	0.05	102
3	0.5	0.1	96
3	0.5	0.15	88
3	1	0	156
3	1	0.05	144
3	1	0.1	136
3	1	0.15	128

Figure 4.21 shows the failure envelope of the embedded strip footing on granular sand with eccentric load having a void at *H/B* =1

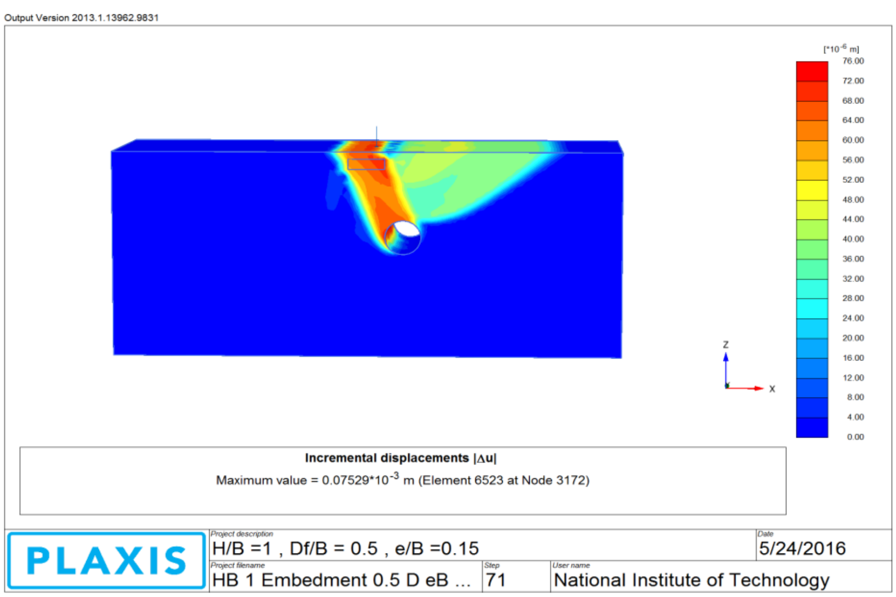

Figure 4.22: Failure envelope of the footing with void at *H/B* = 1

4.8 Introduction to Regression Analysis

Regression analysis is a statistical tool for the establishment of connections between variables. Usually, the investigator tries to determine the causal impact of one variable upon another—the impact of a cost increment upon demand, for instance, or the impact of changes in the cash supply upon the inflation rate. To investigate such issues, the specialist compiles information on the hidden variables of interest and utilizes regression to evaluate the quantitative impact of the causal variables upon the variable that they impact. The investigator likewise normally surveys the "statistical importance" of the assessed formulation, that is, the level of certainty that the genuine relationship is near to the evaluated formulation.

R-squared is a statistical measure of how close the information is to the fitted line. It is otherwise also called as the coefficient of determination, or the coefficient of multiple determination for numerous regression

4.9. Equation formation using regression analysis

The calculated data are plotted and based on the regression analysis, the most reliable equation has been generated and based on the generated equation, and values are predicted for the various combination of input parameters using the predicted model.

4.9.1 Equation of *RF* $_{(L/D)}$ with *L/D*, D_f*/B* and *e/B* parameters

The equation with all the parameters (i.e. *L/D*, D_f/B and *e/B*) has been developed using the regression analysis to give the output of the predicted reduction factor *RF* $_{(L/D)}$, equal to

$$RF_{(L/D)} = \frac{qu\,(\frac{L}{D},\frac{e}{B},\frac{Df}{B})}{qu\,(\frac{L}{D}=\frac{e}{B}=0,\frac{Df}{B})} = 0.239\,\frac{L}{D} + 0.001\,\frac{Df}{B} - 0.385\,\frac{e}{B} - 0.071$$

Where, *RF* (*L/D*) is defined as the ratio of ultimate bearing capacity of shallow strip footing at any location of void with any eccentricity at a particular embedment depth to the ultimate bearing capacity of shallow strip footing without any void and eccentricity at corresponding embedment depth

R-squared value obtained after the linear regression of the above equation comes out to be 0.94

Table 4.10: Deviation between Calculated RF and Predicted RF for *L/D* ratio

Calculated *RF*	**Predicted *RF***	**Deviation (%)**
0.094286	0.1456	-54.4
0.078571	0.1235175	-57.2
0.07	0.101435	-44.9
0.062857	0.0793525	-26.2
0.168224	0.1386	17.6
0.158879	0.1165175	26.7
0.14486	0.094435	34.8
0.135514	0.0723525	46.6
0.153125	0.1316	14.1
0.14375	0.1095175	23.8
0.134375	0.087435	34.9
0.11875	0.0653525	45.0
0.214286	0.2786	-30.0
0.197143	0.2565175	-30.1
0.181429	0.234435	-29.2
0.168571	0.2123525	-26.0
0.257009	0.2716	-5.7
0.242991	0.2495175	-2.7
0.233645	0.227435	2.7
0.224299	0.2053525	8.4
0.25	0.2646	-5.8
0.240625	0.2425175	-0.8
0.225	0.220435	2.0
0.2125	0.1983525	6.7
0.4	0.4116	-2.9
0.371429	0.3895175	-4.9
0.35	0.367435	-5.0
0.328571	0.3453525	-5.1
0.401869	0.4046	-0.7
0.383178	0.3825175	0.2
0.35514	0.360435	-1.5
0.336449	0.3383525	-0.6
0.390625	0.3976	-1.8
0.375	0.3755175	-0.1
0.34375	0.353435	-2.8
0.3125	0.3313525	-6.0

Calculated *RF*	Predicted *RF*	Deviation (%)
0.8	0.6776	15.3
0.75	0.6555175	12.6
0.714286	0.633435	11.3
0.657143	0.6113525	7.0
0.686916	0.6706	2.4
0.654206	0.6485175	0.9
0.607477	0.626435	-3.1
0.560748	0.6043525	-7.8
0.625	0.6636	-6.2
0.59375	0.6415175	-8.0
0.55625	0.619435	-11.4
0.53125	0.5973525	-12.4

4.9.2 Equation of $RF_{(D/L)}$ with D/L, D_f/B and e/B parameters

The equation having the parameters (i.e. D/L, D_f/B and e/B) for the output of the reduction factor $RF_{(D/L)}$ is given by

$$RF_{(D/L)} = \frac{qu\,(\frac{D}{L},\frac{e}{B},\frac{Df}{B})}{qu\,(\frac{D}{L}=\frac{e}{B}=0,\frac{Df}{B})} = -0.87\ \frac{D}{L} - 0.06\ \frac{Df}{B} - 0.68\ \frac{e}{B} + 0.93$$

Where, *RF* (*D/L*) is defined as the ratio of ultimate bearing capacity of shallow strip footing at any diameter of void with any eccentricity at a particular embedment depth to the ultimate bearing capacity of shallow strip footing without any void and eccentricity at corresponding embedment depth

R-squared value obtained after the linear regression of the above equation comes out to be 0.85

Table 4.11 : Deviation between Calculated RF and Predicted RF for *D/L* ratio

Calculated *RF*	Predicted *RF*	Deviation (%)
0.928571	1.303258	23.3
0.857143	1.263291	20.8
0.714286	1.108279	9.8
0.635714	1.041301	4.0
0.654206	0.958543	-4.3

Calculated *RF*	**Predicted *RF***	**Deviation (%)**
0.607477	0.936741	-6.8
0.570093	0.927735	-7.8
0.514019	0.885476	-12.9
0.6875	1.05364	5.1
0.625	1.010509	1.0
0.5625	0.962361	-3.9
0.49375	0.896912	-11.5
0.4	0.808081	-23.8
0.371429	0.805702	-24.1
0.35	0.819672	-22.0
0.328571	0.83606	-19.6
0.401869	0.864235	-15.7
0.383178	0.889043	-12.5
0.35514	0.89456	-11.8
0.336449	0.926856	-7.9
0.390625	0.897989	-11.4
0.375	0.935162	-6.9
0.34375	0.936649	-6.8
0.3125	0.938438	-6.6
0.207143	0.746461	-34.0
0.2	0.821355	-21.8
0.195714	0.934197	-7.0
0.185714	1.058201	5.5
0.247664	1.000661	0.1
0.242991	1.13813	12.1
0.237383	1.322469	24.4
0.228972	1.57369	36.5
0.23125	1.063218	5.9
0.225	1.226158	18.4
0.2175	1.454849	31.3
0.2075	1.796537	44.3

4.9.3 Equation of $RF_{(H/B)}$ with H/B, D_f/B and e/B parameters

The equation having the parameters (i.e. D/L, D_f/B and e/B) for the output of the reduction factor $RF_{(H/B)}$ is given by

$$RF_{(H/B)} = \frac{qu\,(\frac{H}{B},\frac{e}{B},\frac{Df}{B})}{qu\,(\frac{H}{B}=\frac{e}{B}=0,\frac{Df}{B})} = 1 + 0.00385\ \frac{H}{B} \times \frac{Df}{B} + 0.013\,\frac{H}{B} \times \frac{e}{B} + 0.020\,\frac{Df}{B} \times \frac{e}{B}$$

$$+ 0.024\,\{\frac{H}{B}\}^2 + 0.035\,\{\frac{Df}{B}\}^2 - 0.325\{\ \frac{e}{B}\}^2 + 0.417$$

Where, *RF* (*H/B*) is defined as the ratio of ultimate bearing capacity of shallow strip footing at any horizontal displacement of void along the direction of eccentricity with any eccentricity at a particular embedment depth to the ultimate bearing capacity of shallow strip footing without any void and eccentricity at corresponding embedment depth

R-squared value obtained after the quadratic regression of the above equation comes out to be 0.80

Table 4.12: Deviation between Calculated RF and Predicted RF for *H/B* ratio

Calculated *RF*	**Predicted *RF***	**Deviation (%)**
0.4	0.401	-0.25
0.371429	0.483371	-30.1384
0.35	0.54225	-54.9286
0.328571	0.598585	-82.1782
0.401869	0.404251	-0.59274
0.383178	0.458612	-19.6867
0.35514	0.537375	-51.3136
0.336449	0.58674	-74.3921
0.390625	0.463475	-18.6495
0.375	0.509063	-35.75
0.34375	0.596961	-73.6614
0.3125	0.681281	-118.01
0.464286	0.231867	50.05934
0.457143	0.253572	44.53108
0.448571	0.277891	38.04982
0.441429	0.296121	32.91753

Calculated *RF*	**Predicted *RF***	**Deviation (%)**
0.331776	0.482301	-45.3695
0.32243	0.400108	-24.0913
0.313084	0.432236	-38.0575
0.303738	0.401817	-32.2906
0.3375	0.373694	-10.7241
0.33125	0.397086	-19.875
0.31875	0.441173	-38.4074
0.303125	0.424696	-40.1061
0.35	0.3615	-3.28571
0.335714	0.413783	-23.2546
0.314286	0.489574	-55.7737
0.3	0.462588	-54.1958
0.385047	0.245302	36.29302
0.378505	0.270518	28.52982
0.364486	0.321511	11.79052
0.345794	0.387478	-12.0545
0.403125	0.208003	48.40242
0.38125	0.290961	23.68238
0.365625	0.348431	4.702671
0.34375	0.426498	-24.0723
0.5	0.313	37.4
0.478571	0.380964	20.39558
0.452857	0.459456	-1.45719
0.428571	0.530721	-23.8349
0.495327	0.342176	30.91917
0.476636	0.401981	15.66279
0.448598	0.487935	-8.76878
0.411215	0.598465	-45.5357
0.4875	0.398644	18.22692
0.45	0.516187	-14.7083
0.425	0.592075	-39.3118
0.4	0.573088	-43.2719

4.10. Comparison of Reduction Factor (*RF*)

The reduction factor values are obtained for the calculated values obtained from PLAXIS and are compared with the reduction factor obtained from the predictive model equation. The values of the reduction factor obtained are plotted with a line of equality. The points lying on the line or having high proximity to the line of equality are the results which infers that both the calculated and the predicted model are in much accordance. The deviation of sample values up to ± 20 % from the line of equality is considerable within the range of error values.

The values of the calculated and predicted reduction factors for *L/D*, D_f/B, *e/B* parameters are plotted with the line of equality in the Figure 4.22 to check the deviation in the sample values from the line of equality.

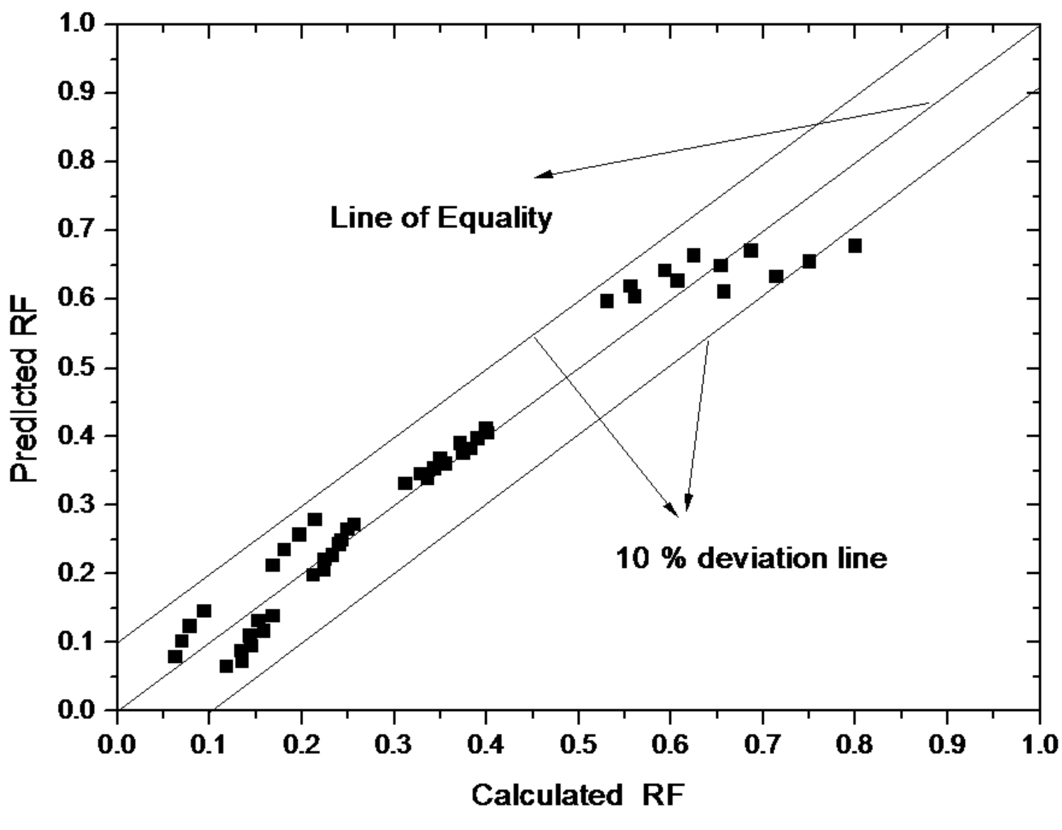

Figure 4.23 Calculated and Predicted RF comparison for *L/D*, D_f/B, *e/B* parameters

The sample data of the analysis with parameters *L/D*, D_f/B, *e/B* parameters are within the range of the 10% from the line of equality. The values of the calculated and predicted reduction factors for *D/L*, D_f/B, *e/B* parameters are plotted with the line of equality in the Figure 4.23

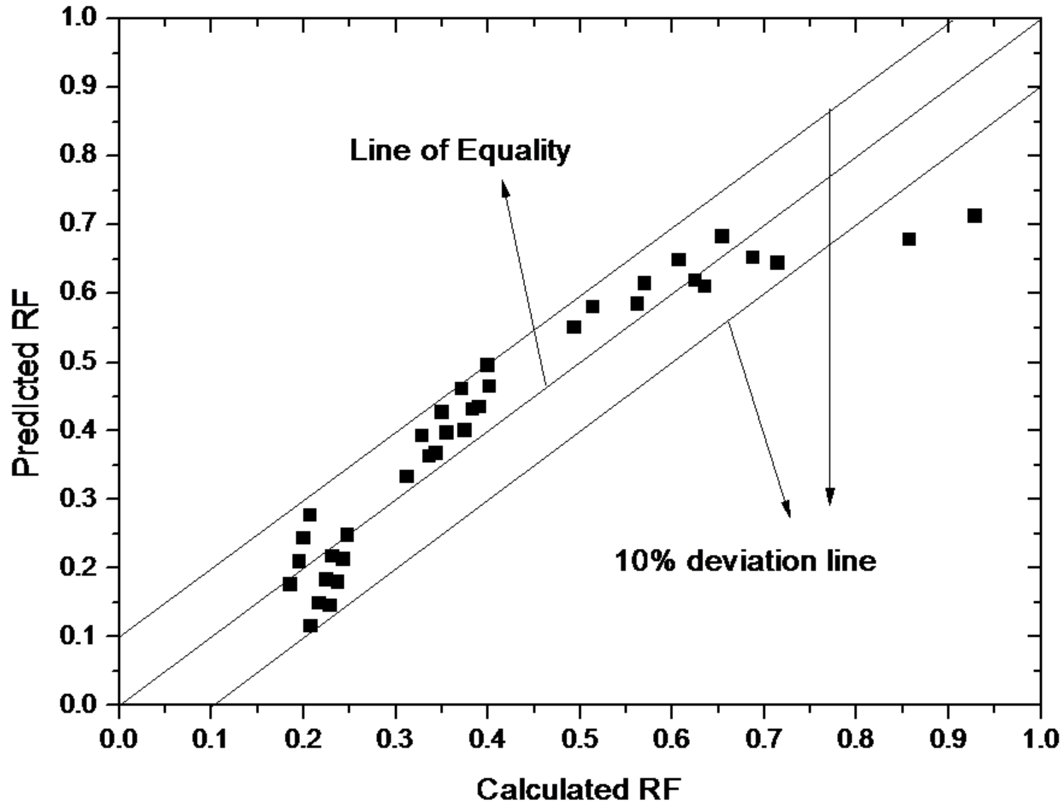

Figure 4.24: Calculated and Predicted *RF* comparison for *D/L*, D_f/B, *e/B* parameters

The data scatter plot of the results obtained from the numerical analysis with parameters *D/L*, D_f/B, *e/B* parameters are within the range of the 10% from the line of equality. The values of the calculated and predicted reduction factors for *H/B*, D_f/B, *e/B* parameters are plotted with the line of equality in the Figure 4.24.

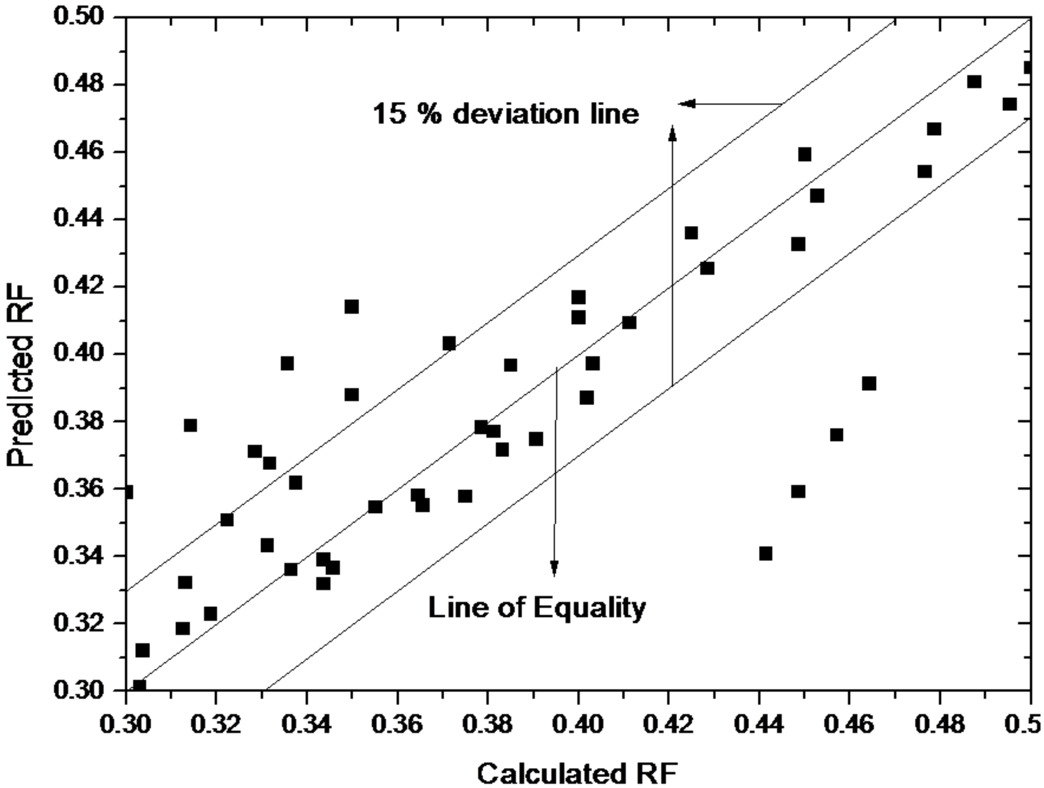

Figure 4.25: Calculated and Predicted *RF* comparison for *H/B*, D_f/B, *e/B* parameters

The plot of the calculated and predicted *RF* (Reduction Factors) having the parameters *H*/*B*, D_f/B, *e/B* are having a data with little more variability, where most of the sample data lies in the range of the 15 % from the line of equality and few sample data values lies within the range of the 50 to 55 %.

CHAPTER -5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

5.1 Conclusions

One hundred and fifty-six numbers of numerical models are simulated using PLAXIS 3D to study the ultimate bearing capacity of the strip foundation supported on granular soil with a flexible void and subjected to a vertical eccentric load. All the Models are simulated on dense sand bed The embedment ratio (D_f/B) is varied from zero to one with an increment of 0.5B. The load eccentricity ratio (e/B) is varied from 0 to 0.15 with an increment of 0.05. The effect of flexible void on the ultimate bearing capacity of the footing has been analyzed by varying the size (D=Diameter of void) in terms of D/L from 0.25 to 0.75, location (L=Location of void below foundation base) in terms of L/D from 1.0 to 4.0 and horizontal distance (H) of the voids from center line of the footing i.e. H/D in the range of 0 to 3.0. Based on the analysis of numerical model results and within the range of parameters studied, the following conclusions are drawn:

• With the increase in the L/D ratio, the bearing capacity of the strip footing increases gradually as the depth of the flexible void increases.

• The effect of flexible void nullifies after the $L/D \geq 4$ as the void reaches beyond the zone of influence of the load acting on the footing.

• With the increase in D/L ratio, the bearing capacity of the strip footing decreases gradually i.e. with the increase in the diameter of the void bearing capacity reduces for a particular L.

• With the increase in the H/B ratio, the bearing capacity increases with the embedment depth and it decreases with the eccentricity ratio for a particular embedment.

• A comparison between the reduction factors obtained from the numerical model results shows a variation of ±20% or less. But in some cases, the deviation is about 50 to 55%.

5.2 Scope of the future work

The present thesis pertains to the study on the effect of flexible voids on the bearing capacity of eccentrically loaded strip footing. The future research work may consider the below mentioned criteria's:

- One reduction factor may be developed considering these three parameters i.e. *L/D*, *D/L* and *H/B*
- Effect of voids on Settlement, pattern of failure, stress distribution of centric inclined and eccentrically inclined loaded footing can be studied.
- The present work can be extended considering other densities.
- The present work can be extended to foundations on other type of soils.
- The present work can be extended to soil condition with reinforcement.
- The present work can be extended to seismic and dynamic analysis.
- The present work can be extended to rigid void.

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