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Numerical Assessment of Isolated Footing Capacity due to its Size and the Impact of Neighboring Foundation

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ABSTRACT

Shallow foundations are uses for safe transmission of structural load to the ground considering soil bearing capacity and allowable settlement. In this research, an empirical analysis is present by using Terzaghi and Meyerhof model. Which is compared with numerical analysis using PLAXIS 3D Foundation. Bearing capacity determined by both cases matched well. The purpose of the study is to predict the maximum allowable stress capacity of shallow foundation in different conditions and establish relationships between stress and settlements for different footing dimensions under various circumstances, as well as the impact of pressure bulb overlapping of two adjacent footing. There are some notable findings are found in this study such as Ultimate stress bearing capacity of soil under allowable settlement varies if two adjacent footings are placed 1.5 m apart. Similar results have been found by varying spacing 2 m & 2.5 m. Sizes of footing may have insignificant effect on spacing between two adjacent footings. And footing may act as an isolated footing in 3 m away from another footing on sandy soil and 2 m away from another footing on clayey soil.

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1. Introduction

Foundation is the lowest load bearing part of any structures. Shallow and deep foundation are the two types of foundation, which distribute structures load to its underlying soil. Foundations should be designed for taking care of soil at all depths pressures and for tolerating total and differential movements. The ability of soil to hold any engineered structure pressure on soil without shear failure is known as bearing capacity. Settlements of the foundations are going to be within acceptable limits can't make sure by applying an impact pressure. Settlement analysis should generally be performed because most structures are sensitive to excessive settlement. The theoretical maximum pressure which may be supported without failure is known as Ultimate bearing capacity; allowable bearing capacity can be found by dividing ultimate bearing capacity divided by an element of safety. On soft soil location under loaded foundations sometimes large settlements may occur without actual shear failure occurring; in that type of cases, the allowable bearing capacity is predicated on the utmost allowable settlement [1].

Geotechnical engineers are often deals with non-homogeneous layered soil under foundation, but for engineering purposes they simplified in representation as homogeneous layers. Layered soil failure mechanism depends on the soil properties and thickness of every layer. Layer which is thicker and consists of weak soil the failure mechanism could also be limited within these layer only and the remaining layers has no influence on it. The failure mechanism should be considered for two or more layers for other cases [1].

Finite element analysis is a numerical technique. In this system all the complexities, like shape variations, boundary conditions and loads are keep same but the obtained results are approximate. Nowadays, it's gaining engineers attentions for its variety and flexibility. Geotechnical and structural analyzation within the deep excavations like the soil properties, details of structures, construction sequences, and supply necessary information which is required for design purpose can be done by Numerical analysis. This research has been done by using PLAXIS 3D FOUNDATION [1].

There are two main parts of foundation design, one is the ultimate bearing capacities of the soil under the foundation, and other is tolerable settlement which can withstand by footing without affecting the superstructure. Determining the value of load that can handle by the soil under the foundation before shear failure, is the aims of the ultimate bearing capacity. Researches on ultimate bearing capacity are often administered using either analytical simulations or experimental analyzation. The numerical simulation can be done using theory of plasticity or finite element analysis, while the experimental analyses can be done by making prototype, model and full-scale tests. While theoretical results matched with experimental results then the solution is satisfactory. Soil layer assumed homogeneous and soil parameters are assumed remain constant for bearing capacity analysis by analytical solution and Terzaghi's bearing capacity theory, where results matched well with each other's. However, in some cases where the soil parameters vary with depth, most of those theories can't be used, for that the analytical solutions that take into consideration the non-homogeneity shows inaccurate results. There are two types of layered soil profiles, one is naturally deposited and other is artificially made. The soil considered as homogeneous. The ultimate load failure surface within the soil depends on the shear strength parameters of the soil layers, such as; soil layer thickness, footing shape, and footing size. So, it is important to work out the profile and to calculate the bearing capacity accordingly [2].

Two types of layered soil profiles were taken, where a strong layer situated over a weak layer, and vice versa. Within the literature, over the last four decades, several reports are often found handling the matter of foundations situated over layered soils. For developing empirical formula to predict the ultimate bearing capacity of footings, researchers analyze on the results of prototype in laboratory model testing. In this chapter some relevant review about these reports are presented. Now-a-days Finite element analysis is used extensively for geotechnical problem solutions [3]. Conventional finite element analyses are frequently used to predict the bearing capacity of multilayered soils (Griffiths, 1982; Burd and Frydman, 1997). Various elasto-plastic parameters are main reason for the steadiness of structures facing natural phenomena. The anisotropy of soil shear strength and stiffness has been recognized as a crucial thing about many sorts of ground deformation and failure issues (Nishimura, 2005). Soil-water interaction, Over consolidation ratio (OCR), bonding effect or structured soil also are significant factors to effect on bearing capacity of shallow foundation on clayey soil. Many researches are conducted to gauge static and dynamics properties and make many co-relations with other soil index properties of soil [1].

The last three decades have witnessed a tremendous growth in the numerical method. For this, it is possible to obtain more realistic and satisfactory results of the shallow footing design to make it more economical. So many works are already found on this numerical method applied on strip footing bearing capacity and settlement. Settlement modelling of raft footing founded on Oderekpe/Abakaliki shale in south east region of Nigeria [4]. Strength Characterization of foundation soils at federal university Lokoja based on standard penetration tests data [5]. Empirical and numerical prediction of settlement and bearing capacity of foundations from SPT data in North-West region of Nigeria [6]. Bearing capacity and settlement analysis of closely spaced shallow foundations with various footing geometry on multi-layered soils [7]. Ultimate bearing capacity of two interfering strip footings on sand overlying clay [8]. Study of Tilt on Adjacent Strip Footings [9].

The Mohr-Coulomb model [10–12] is a linear elastic and perfectly plastic soil model that is used to analyze soil behaviors in elastic zones. Hooke's law of isotropic elasticity is followed in the linear elastic part of the model and the perfectly plastic part is constructed on the Mohr-Coulomb failure criterion. The model requires the following material properties: cohesion, friction angle, dilatancy angle, unit weight, permeability and modulus of elasticity, which are well known to most geotechnical engineers and can be obtained from basic tests on soil samples. Both effective and undrained parameters can be considered depending upon the drainage type of the model [13].

In 1953 Button analyze on bearing capacity of a strip footing resting on two layers of clay soil. Both layers are considered consolidated nearly equivalent. For calculation of ultimate bearing capacity of foundation he assumed that the ultimate load failure surface is cylindrical, and curve lies at the edge of the footing. Based on the upper soil layer and on the ratio of the cohesion of the top/bottom clay layers the bearing capacity factors are used [14].

In 1969 Meyerhof and Brown research on foundations staying on a stiff clay layer which is situated over a soft clay layer, and then the soft layer situated over a stiff layer. They assumed that footing fails by punching via top layer for first case, and fails with full development of the bearing capacity of the bottom layer for second case. Acceptable modified bearing capacity factors got from equations and charts, found from the empirical relationship which is found from experimental results. The results of the research were summarized in charts, for utilizing during calculation of bearing capacity of layered clay foundations, but these results are strongly suffering from the characteristics of the clay tested because these are experimental. The aim of this research is to present the results in a series of model footing which tests administered on two-layered clay soils, and therefore the models have many restrictions. They're used only one types of clay, but strength of the clay varied, the deformation properties remained constant. Using rigid strip and circular footings with rough bases this research completed and only surface loading applied. During these studies were made shear strength of the clay assumed as un-drained. Footings resting in homogeneous clay a series of tests also conducted. They found that the failure pattern under a footing is a function of the physical mode of the clay rupture, which depends on the structure of the clay. The mechanism of failure of the structure situated on the clay isn't explained by conventional Mohr-coulomb concepts of cohesion and friction [15].

In 1971 Ohri analyze on the effect of disturbance of two neighboring planes and rough square footings under to vertical load which is situated in cohesion less soil. The failure mechanism indicates fourfold symmetry and displacement is orthogonal to the sides. But it is often said that this analyzation will provide a useful start line for a far better alternative boundary solution [16].

In 1974 Meyerhof research in the case where sand layer situated over a clay layer. He used dense sand over soft clay and loose sand over stiff clay. Results found on circular and strip footings and field data were compared with model tests results of the analyses of various modes of failure. While dense sand situated over a soft clay deposit, the failure mechanism was assumed as nearly truncated pyramidal shape, pushed into the clay in order that, for the case of general shear failure, the friction angle of the sand and the un-drained cohesion of the clay are integrated within the combined failure zones. Using this theory, for calculating the bearing capacity of strip, and circular footings staying on dense sand over soft clay, semi-empirical formulas were developed. He carried out some model tests on strip and circular footings on the surface and at shallow depths for the soil profile dense sand layer overlying clay. Those tests result and the observations of field were found to accept as true with the theory. The sand mass under the footing failed laterally by squeezing at an ultimate load while loose sand situated on stiff clay. Formulas were developed for the ultimate bearing capacity of strip and circular footings. Model tests were performing on strip and circular footings, and it was found that the results also agreed with the developed theory. It was found from theory and those test results that the impact of the sand layer thickness under the footing depends mainly on the bearing capacity ratio of the clay to the sand, the friction angle of the sand, depth and shape of the foundation. This research is restricted to vertically loaded footings only, it doesn't include eccentric or inclined loads, and it's only describing about soil profile sand over clay, and did not give any solution for clay over sand [17].

In 1985 Georgiadis and Michalopoulos presented a numerical method for determining the bearing capacity of shallow foundations resting on layered soil, which could be any combination of cohesive and non-cohesive layers. Several potential failure surfaces were analyzed and then minimum material factor for which foundation is stable was chosen. Variety of semi empirical solutions for homogeneous and two-layer soil profiles, experiments and other numerical methods including finite elements, and comparisons between the results found using this method, showed the validity of the proposed method. Semi-empirical methods for the calculation of the bearing capacity of shallow foundations on two-layer soil profile are based on the results of experimental investigations. Most of them are restricted to variety of limited cases, and can't cover any layered soil profiles; moreover, the bearing capacity computed with the varied semi- empirical formulas are usually scattered. Within the case of quite two layers during a profile, the bearing capacities are often computed with a finite element analysis or numerical analysis [18].

In 2013 Verma & Kumar have studied on different layered soils, for an equivalent thickness and sort of soils in upper layer (fine gravel) lower layer (sand), if size of square test plates increases bearing capacity increases and settlement decreases [19].

In 2013 Marto & Oghabi have analyzed on geo-grid presence within the soil and makes the correlation between the applied pressure & settlement. They found their behavior is almost linear until getting to the failure stage [20].

2. Research significance

The designers will find important information about choose footing size and spacing between two adjacent footings in constructing shallow foundation on layered soil through this research. The objectives of this research are:

- To predict the utmost allowable stress capacity of shallow foundation in several conditions.
- To predict minimum required spacing between two adjacent footings for acting as isolated footing.
- To establish relationships of Stress, Settlements, Footing dimensions, Two adjacent footing spacing.
- Comparing results of Numerical analysis and traditional methods.

It is essential to notice that the models were simple and only require minimum information. Furthermore, the research also helps to predict about the bearing capacity, settlement, size of the footing, minimum required spacing between two adjacent footings under different condition.

3. Methodology

Theoretically a precise analysis of bearing capacity and settlement is so lengthy because of data collection from field and work with them in laboratory and analysis on them to find a result is time-consuming. Besides, there are higher degree of indeterminacy and unpredictable behaviors of soil. Analysis can do theoretically in many ways considering the empirical relations and suggestions offered by numerous authors. This chapter deals mainly with the collection of soil parameters, development of soil model to estimate of ultimate load bearing capacity of footing and the settlement of footing by empirical and as well as numerical system, and finally comparison between empirical and numerical analysis result. Numerical analysis was performed by PLAXIS 3D FOUNDATION to obtain bearing capacity and settlement of footing in different soil conditions. To predict the bearing capacity, settlement, size of the footing, minimum required spacing between two adjacent footings under different conditions numerical analysis has been performed. The research work has been progressed in following steps:

- Allowable bearing capacities of shallow foundations are calculated by conventional method as well as numerical method.
- Settlements of shallow foundations are calculated by conventional method as well as numerical method.
- Stress-Settlement graph is plotted for different spacing and the loads against 50 mm settlement are considered to be the allowable settlement of shallow foundation.
- Stress-Dimension graph is plotted for different spacing and the loads against 50 mm settlement are considered to be the allowable settlement of shallow foundation.
- Stress-Distance graph is plotted for different dimension and the loads against 50 mm settlement are considered to be the allowable settlement of shallow foundation.

Afterward, evaluating several possible behavior patterns of shallow foundation have been generalized as outcomes.

3.1. Different types of soil parameters

For the estimation of ultimate bearing capacity and settlement of shallow foundation in conventional method, four different types of soil comprising layers of different parameters use as representative samples. To represent a generalized foundation response, four soil profiles are considered based on the contribution of Medium stiff clay, Dense sand and Medium dense sand as shown in Figure 3.1. Soil type-1 and soil type-2 which are medium stiff clay over dense sand, are used for bearing capacity calculation by conventional method and as well as numerical method for 50 mm allowable settlement, and finally the results are compared. Soil type-3 and soil type-4 which are medium dense sand over medium stiff clay, are used for settlement calculation by conventional method and as well as numerical method, and finally compare the both result. The considered footing thickness is 0.5 meters that is placed at a depth of 2 meters from ground surface. The soil layer is considered as 10-meter depth. Where, upper layer is equivalent to 2 meters + 0.5 meters thickness of footing + 2 times of footing dimension. The rest is considered as lower soil layer.

We use these parameters for both numerical simulation (using PLAXIS 3D FOUNDATION) and empirical method (using Terzaghi bearing capacity formula). For the allowable bearing pressures and settlement of shallow foundations, footing plan dimension of 2 m by 2 m by .5 m for length, breadth and depth respectively were assumed with safety factor 3 for soil type 1 & 3. Footing plan dimension of 3 m by 3 m by .5 m for length, breadth and depth respectively were assumed with safety factor 3 for soil type 2 & 4 [26].

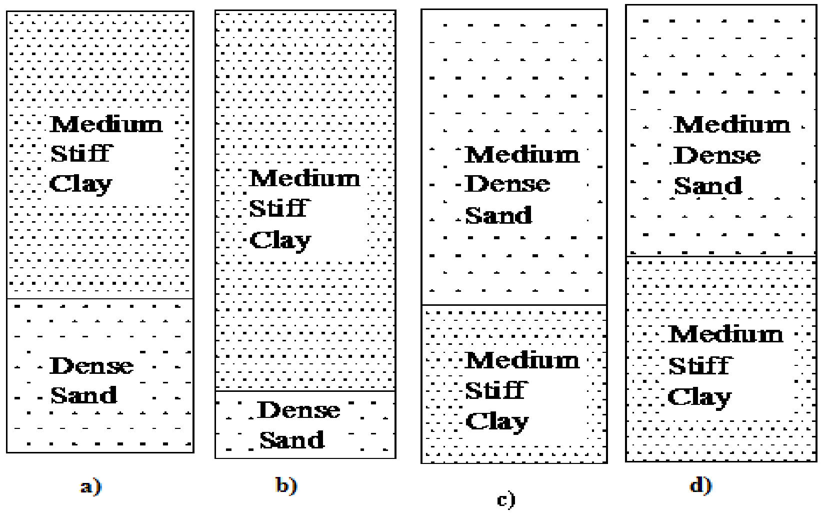


Fig. 1. Different types of layered soil a) Soil type-1, b) Soil type-2, c) Soil type-3, d) Soil type-4.

Table 1
Different soil parameters for this research.

Parameters	Unit	Medium Stiff Clay	Medium Dense Sand	Dense Sand	Reference
Angle of internal friction (Φ)	Degree	25	35	40	[21]
Modulus of elasticity (E)	kN/m^2	10,000	35,000	70,000	[22]
Soil unit weight (γ)	kN/m^3	16	16	18	[23]
Poisson's ratio (ν)	-	0.35	0.3	0.45	[24]
Soil Cohesion (C)	kN/m^2	25	1	2	[25]
Soil Model	Mohr-Coulomb				
Soil Behavior	Undrained				

3.2. Bearing capacity calculation through conventional methods

In layered soil profiles, soil unit weight, angle of internal friction and cohesion are not constant throughout the depth. The ultimate failure surface may extend through two or more of the soil layers. Within each layer in layered soil deposits, the soil can be assumed to be homogeneous while the strength properties of adjacent layers are generally different.

Meyerhof and Hanna proposed a semi-empirical technique, based on small scale tests, to solve the bearing capacity of a sand layer overlaying a clay layer [27]. As referred by Murthy et al. [28], finite element method or numerical limit analysis were utilized by Burd and Frydman to obtain the bearing capacity of two-layer clay foundation with distinctly different strength [29].

Terzaghi (1943) was introduce a widespread theory for evaluating the safe bearing capacity of shallow foundation with unsmooth base and introduced three types of bearing capacity calculation system based on failure pattern. They are general shear failure, local shear failure and punching shear failure [30].

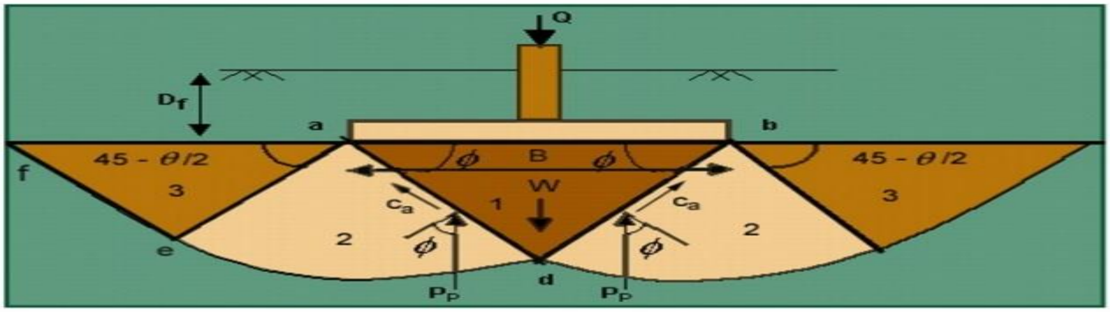


Fig. 2. Terzaghi’s bearing capacity theory [31].

The ultimate bearing capacity for local shear failure for square footing is obtained as follows,

$$q_u=0.867C'N_c'+\gamma D_f N_q'+0.4\gamma B N_\gamma'$$

Notation:
q_u = Ultimate bearing capacity of the underlying soil,
C' = Cohesion of underlying soil, [25]
γ = Soil unit weight [23],
B = Dimension of each side of the foundation,
D_f = Depth of foundation,
N_c', N_q', N_γ' = Modified bearing capacity factors [32]

Result of bearing capacity:

Soil Type 1: By conventional method, q_u= 528.8 kN/m^2 & by Numerical analysis, q_u= 550 kN/m^2

Soil Type 2: By conventional method, q_u= 444 kN/m^2 & by Numerical analysis, q_u= 360 kN/m^2

It is found that bearing capacity determined by the conventional methods and numerical simulations matched well.

3.3. Settlement calculation through conventional methods

Structural damage and disturbance to a building frame can caused by excessive settlements, such as sticking doors and windows, cracks in tile and plaster, and excessive wear or equipment failure from misalignment. It is necessary to investigate both shear resistance of base (ultimate bearing capacity) and soil settlements for the stability of structure [2].

The types of foundation settlement are: Immediate settlement, Primary settlement, and Secondary compression (creep). Primary settlement further divided into two types [32],
Normally consolidated clay: The present effective overburden pressure is the maxi-mum pressure that the soil has ever experienced in its lifetime.
Over consolidated clay: The present effective overburden pressure is less than that which the soil experienced in the past.
For Normally consolidated clay:

$$S_c = \frac{C_c H}{1+e_0}\log_{10}\frac{\delta_0+\Delta\delta}{\delta_0} \quad [32]$$

For calculation of settlement taking three dimensional effect into account,

$$\Delta\delta_{avg} = \frac{\Delta\delta_t + 4\Delta\delta_m + \Delta\delta_b}{6} \quad [32]$$

Notation,
C_c = Compressibility Index (0.27), [32]
H = Height of clay layer,
e_o = Initial void ratio (0.9), [32]
δ_o = Effective overburden pressure, $\delta_o = \gamma(D_f + H)$,
$\Delta\delta$ = Additional stress due to structure,
$\Delta\delta_t$ = Additional stress due to structure at top,
$\Delta\delta_m$ = Additional stress due to structure at mid height,
$\Delta\delta_b$ = Additional stress due to structure at bottom,

For Soil Type 3:
H = 3.5m, h= (6.5+3.5/2) =8.25m, $\delta_o = \gamma h$ = (16x8.25) = 132 kN/m^2.

Table 2
Data for calculation of additional stress due to structure by taking three dimensional effect into account.

m=L/B	h,(m)	b=B/2	n=z/b	I4	$\Delta\delta_0$ (kN/m^2)	$\Delta\delta$ (kN/m^2)
1	6.5	1	6.5	.035	700	30.8
1	7.375	1	7.37	.044	700	24.5
1	8.25	1	8.25	.027	700	18.9

Notation,
m = length by width ratio,
h = depth,
$\Delta\delta_0$ = Structure Stress (Previous),
$\Delta\delta$ = Structure Stress (New),
I4 = Factor based on m and n value [32],
Here, $\Delta\delta avg$ = (230.8+4*24.5+18.9)/6 =24.6 kN/m^2.

For Soil Type 4:
H = 4.5m, h= (5.5+4.5/2) =7.75m, $\delta_o = \gamma h$ = (16x7.75) = 124 kN/m^2.

Table 3
Data for calculation of additional stress due to structure by taking three dimensional effect into account.

m=L/B	h,(m)	b=B/2	n=z/b	I4	$\Delta\delta_0$ (kN/m^2)	$\Delta\delta$ (kN/m^2)
1	5.5	0.75	7.73	.035	800	28
1	6.62	0.75	8.83	.024	800	19.2
1	7.75	0.75	10.33	.019	800	15.2

Here, $\Delta\delta avg$ = (28+4*19.2+15.2)/6 =20 kN/m^2

Result of settlement Calculation:

For soil type-3: Using Conventional method, S_c=39.9 mm & using Numerical analysis, S_c=39.6 mm.

For soil type 4: Using Conventional method, S_c=41.5 mm & using Numerical analysis, S_c=46 mm.

It is found that settlement determined by the conventional methods and numerical simulations matched well. Now we can take PLAXIS 3D FOUNDATION results as standard and our procedure is correct because it's bearing capacity and settlement values matched with well-established empirical results.

3.4. Geometric model and analysis

A square footing is loaded vertically at exactly its center point for ignoring any eccentrically effect on foundation. The footing is 2 m below from soil surface and the thickness of footing is 0.5 m and total soil profile taken as 10 m thick with varying top and bottom layer thickness and soil layer types.

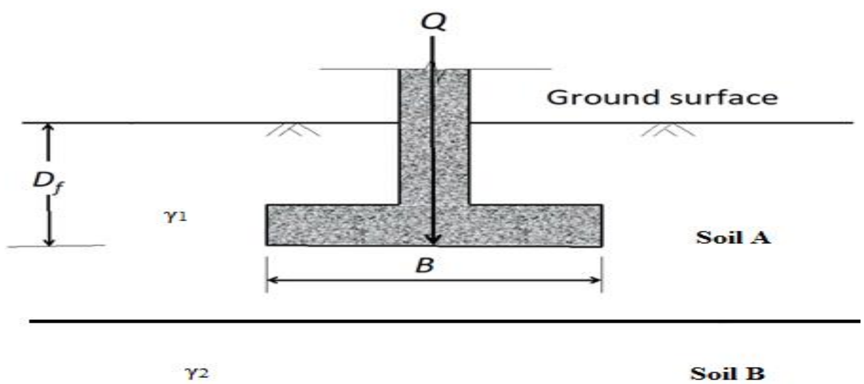


Fig. 3. Shallow Footing under Vertical Load [33].

Similar arrangements are prepared for different types of soil for models development and analysis in PLAXIS 3D FOUNDATION software [34].

Step-1: Work planes are generated (Fig. 4) as horizontal planes at a certain vertical level in which geometric points, lines and loads can be defined.

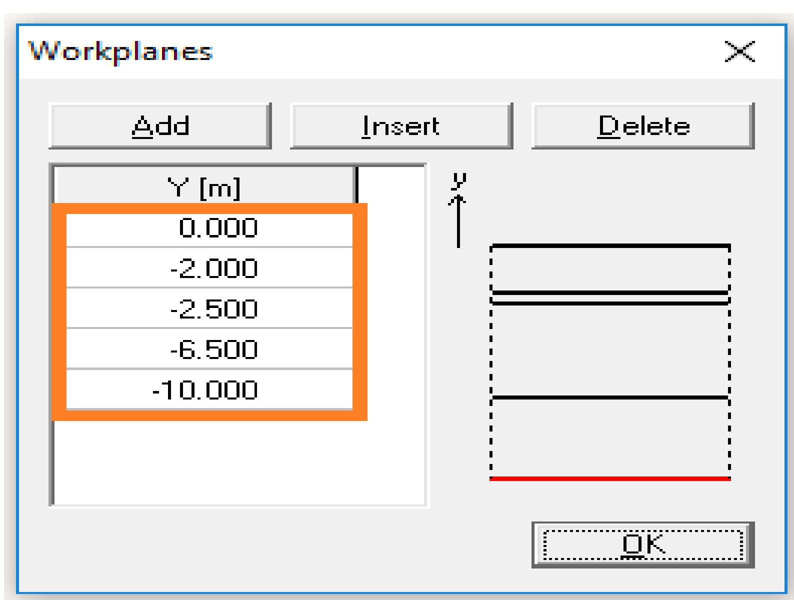


Fig. 4. Workplanes generation.

Step-2: Boreholes are designed in the geometry model (Fig. 5) to define the considered soil layers.

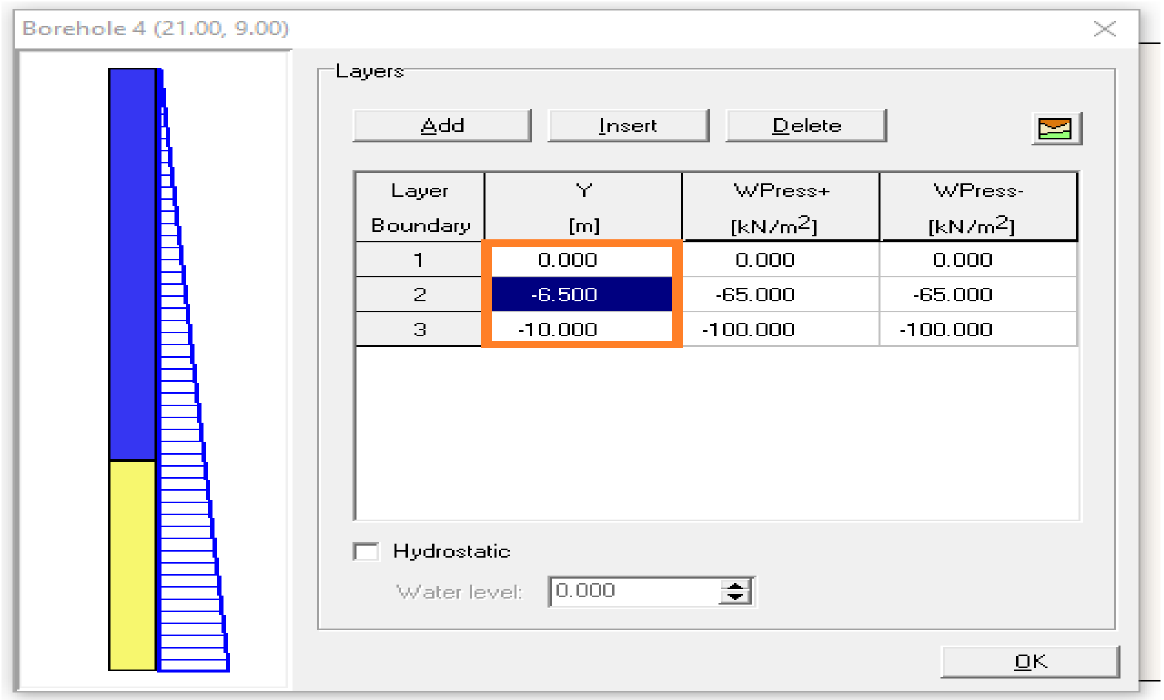


Fig. 5. Boreholes generate.

Step-3: As shown in (Fig. 6) the soil parameters at different layers are applied.

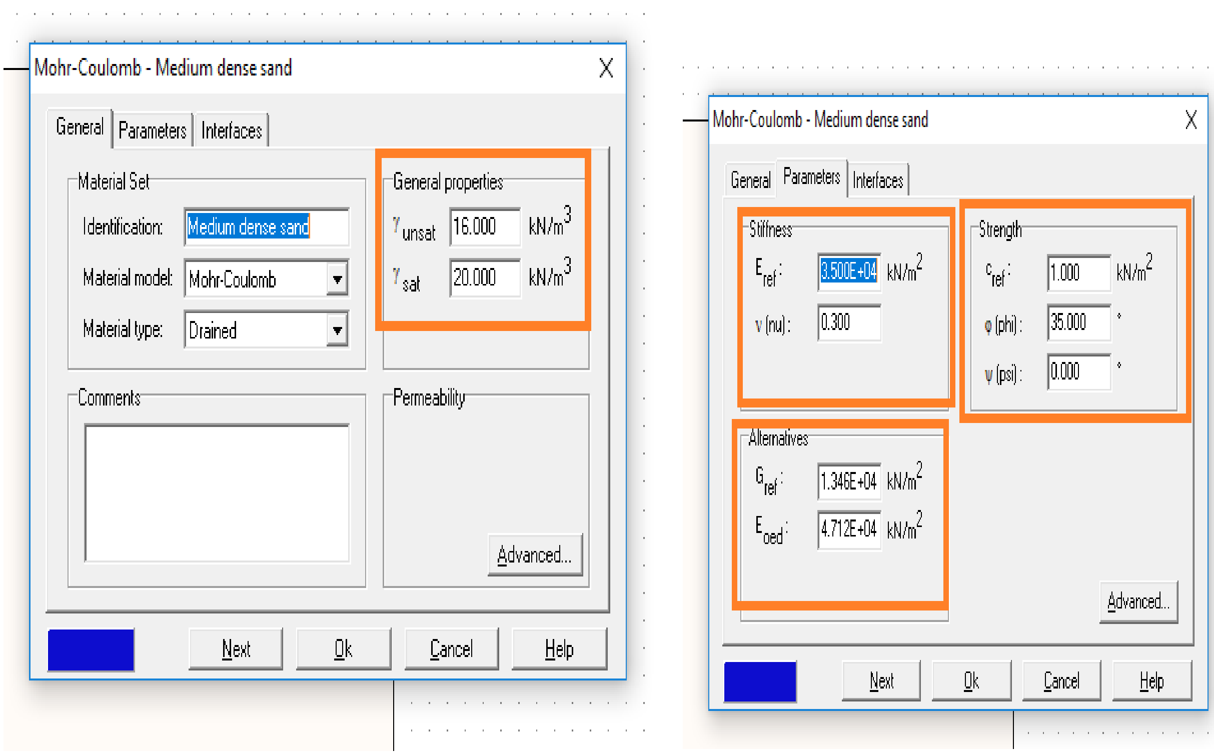


Fig. 6. Soil layer data a) General inputs of soil, b) Parameters input of soil.

Step-4: The footing properties are also applied as showing (Fig. 7)

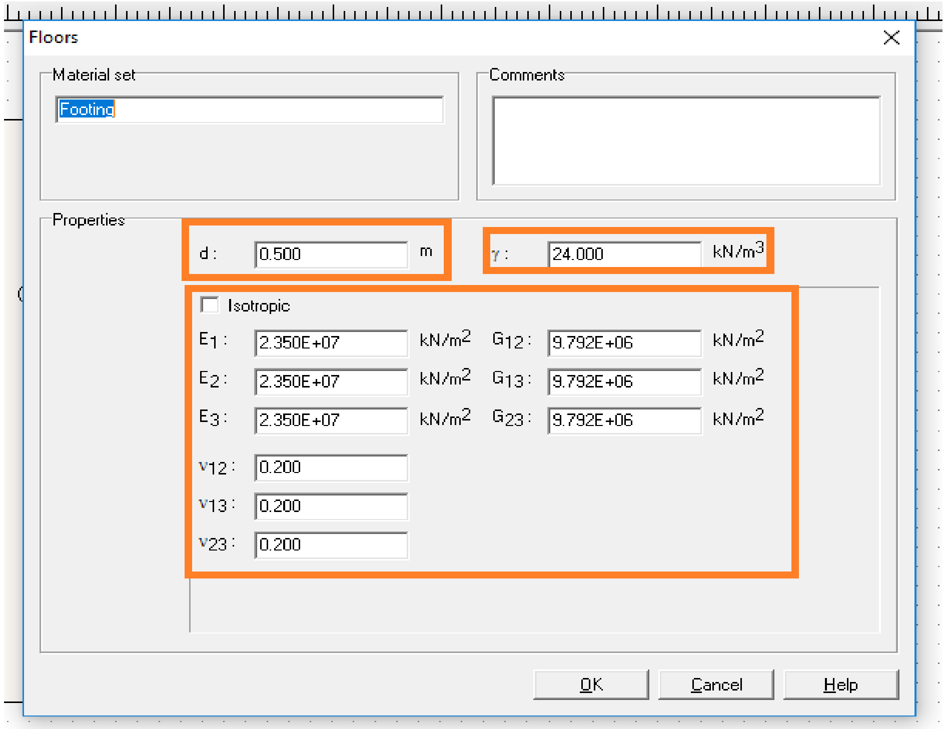
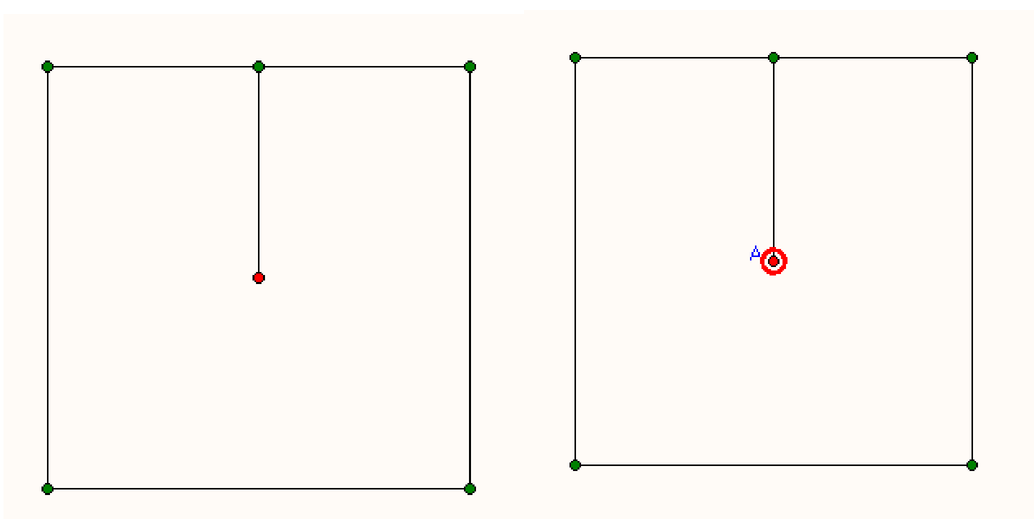
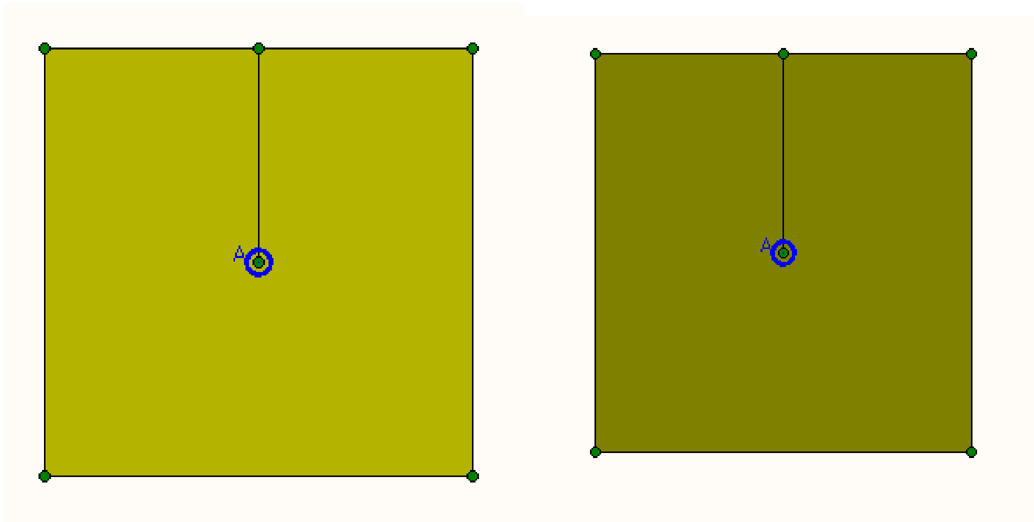


Fig. 7. Footing's property input interface.

Step-5: (Fig.8) represents the geometric boundary of footing and load assignment location.



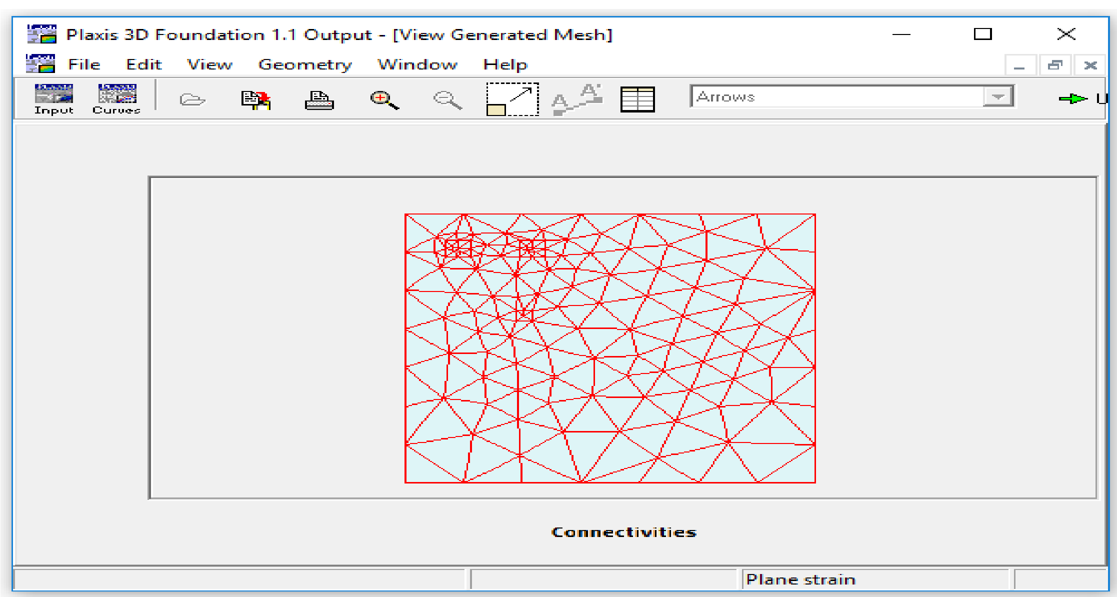
a) b)



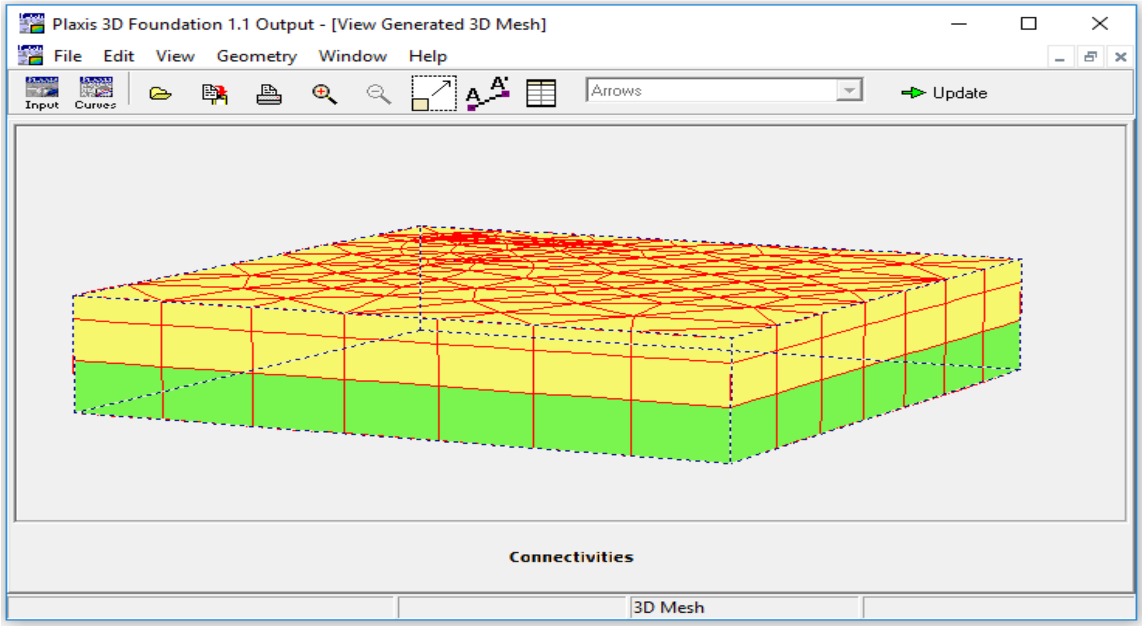
c) d)

Fig. 8. System of load assigning. a) Geometry lines, b) Assigning load c) Assigning floor, d) Assigning footing as floor.

Step-6: To perform finite element calculations, the geometry has to be divided into small elements. A composition of finite elements is called finite element mesh. When the geometry model is fully defined and material properties have been assigned to all soil layer and structural object, it is recommended to generate 2D and 3D mesh as shown in (Fig. 9). With the 3D mesh generation, the geometry modeling process is complete. To illustrate the phases of construction as well as loading stages, it is being proceeded into the "Calculation" mode afterward.



a)



b)

Fig. 9. Generation of mesh for finite elements analysis. a) 2D mesh generate b) 3D mesh generate.

Step-7: In calculation mode different phases are generated like excavation, footing loading etc. which are shown in (Fig.10).

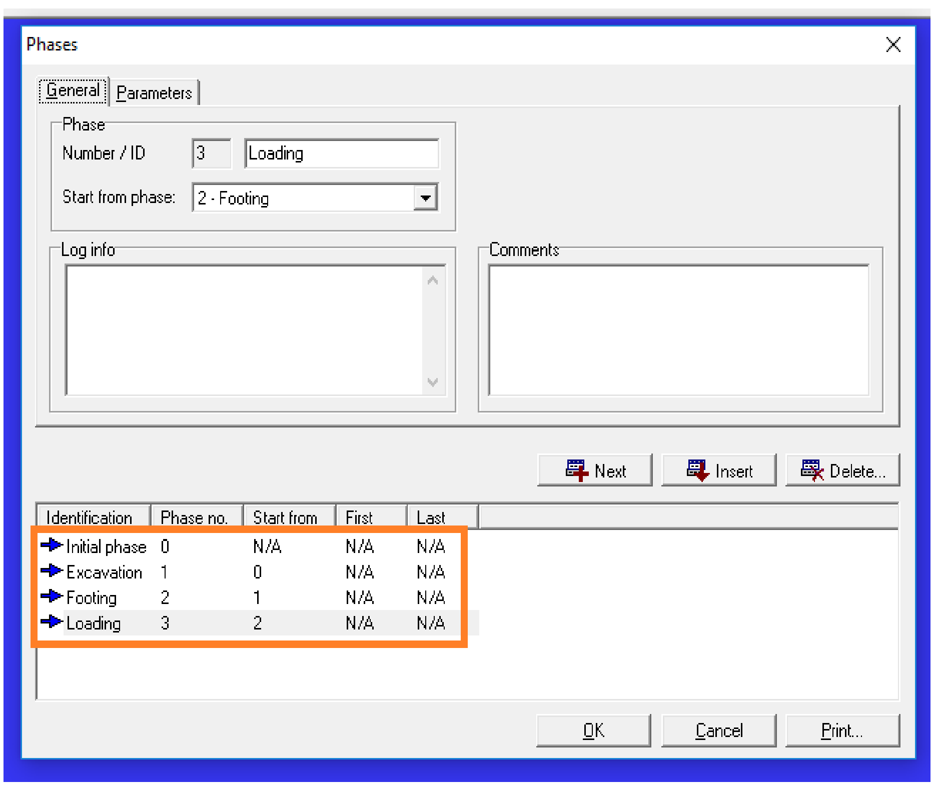


Fig. 10. Creating calculation phases.

Step-8: Load is applied on the shallow footing (Fig. 11) & (Fig. 12).

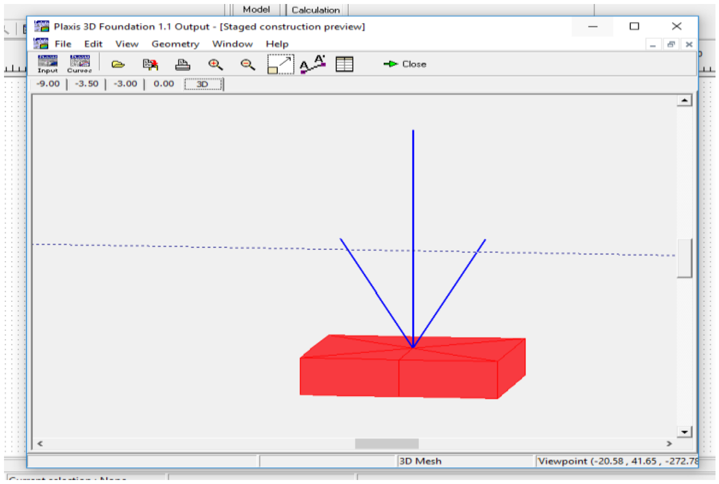
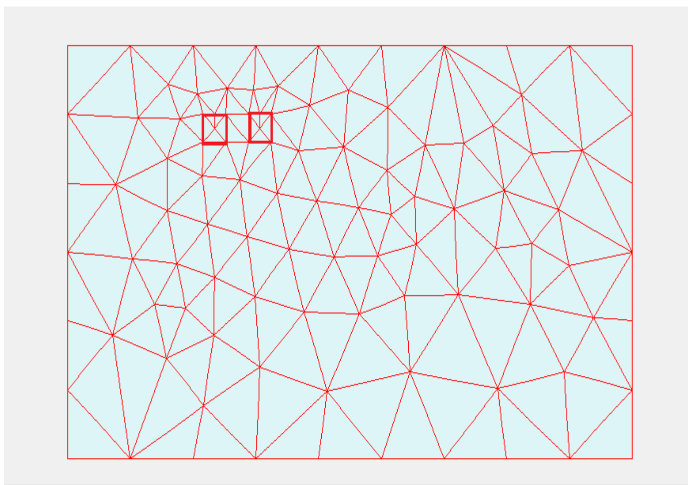
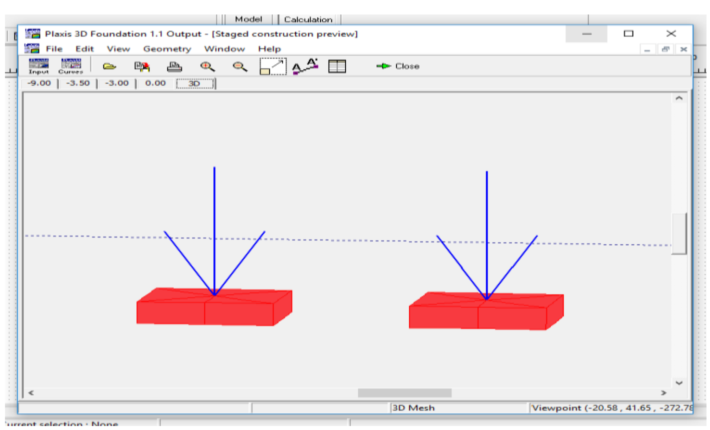


Fig. 11. Preview of an isolated footing and load.



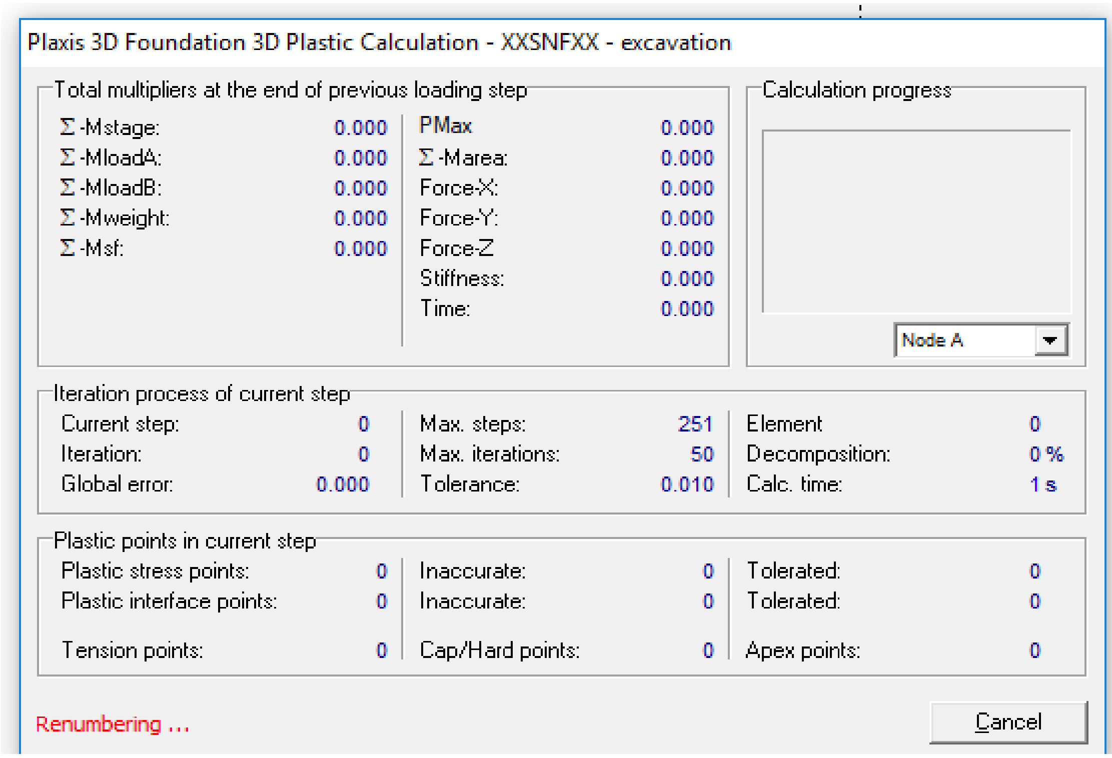
a)



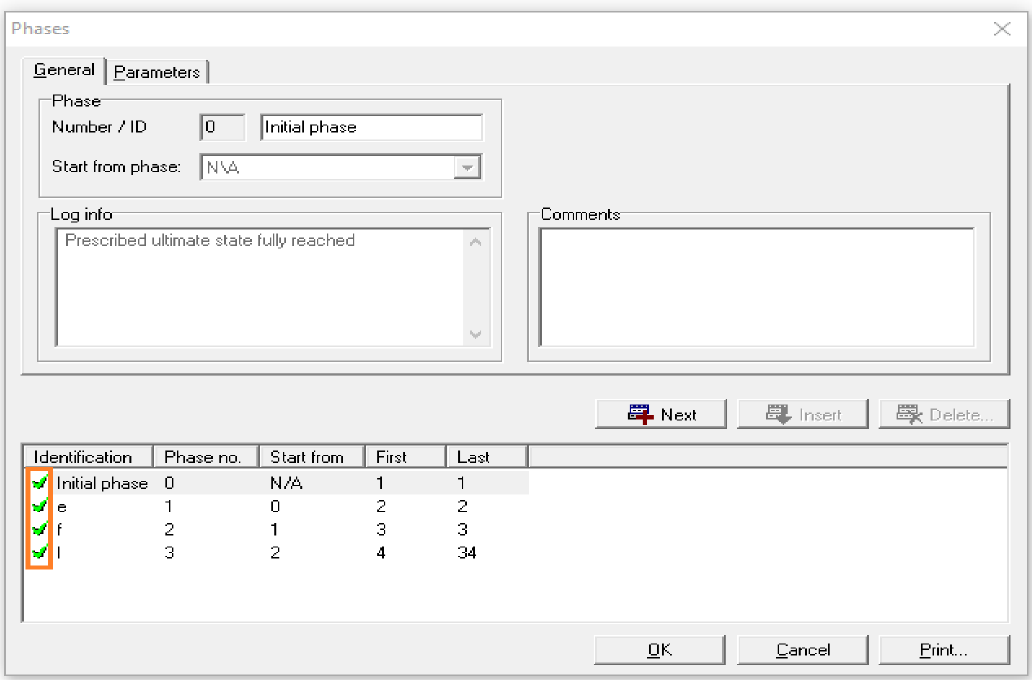
b)

Fig. 12. Preview of two adjacent footing. a) 2D mesh of two footing, b) Preview of two adjacent footing and load.

Step-9: Calculation proceeds which is shown in (Fig. 13).



a)



b)

Fig. 13. Calculation phase a) Calculations sheet, b) Confirmation of correct calculations.

Step-10: Finally the settlement outputs are generated (Fig. 14).

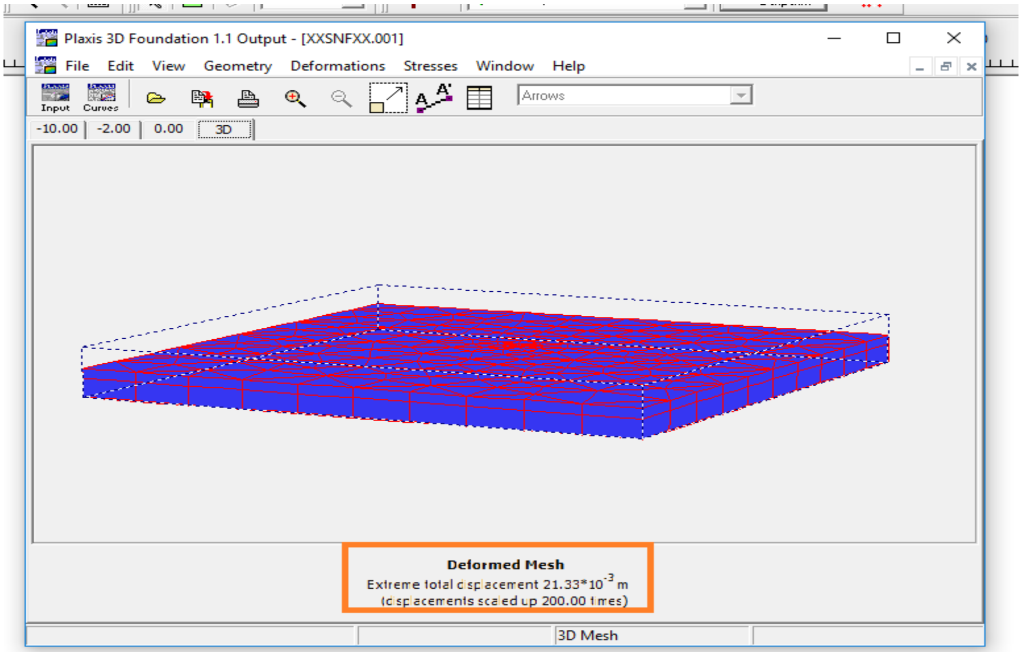


Fig. 14. Settlements of Footing.

For different magnitude of applied loads, different settlements are found which are graphically presented in Result and Discussion chapter.

4. Results and discussions

4.1. Maximum allowable stress determination

Stress is a physical quantity that expresses the internal forces that neighboring particles of a continuous material exert on each other. The maximum average contact stress between the foundation and the soil without failure is known as bearing capacity of soil. Using PLAXIS 3D FOUNDATION maximum stress for different type of soils and different size of footings are determined by trial method. Different load is applied on different size of footing in different soil condition for finding maximum load bearing capacity in each condition under maximum allowable settlement (50 mm). Finally, the ratio of maximum load in allowable settlement and footing area is represented as maximum allowable stress.

As shown in Table 4 & 5 as the footing size increases (from 2 x 2 to 3 x 3) the allowable stress capacity of soil decreases for all types of soil considered in this study. The data of the table also indicates that the presence of clayey soil in considerable depth shown significantly less bearing capacity under allowable settlement. Based on allowable settlement the soil load bearing capacity of considered soil can be arranged as:

Dense Sand> Medium Dense Sand above Dense Sand> Medium Stiff Clay above Dense Sand> Sandy Clay> Medium Dense Sand above Soft Clay.

Table 4
Ultimate Stress analysis of footing dimension (2 x 2) for different soil profile.

Soil Type	Load (kN)	Settlement (mm)	Ultimate Stress under allowable settlement of 50 mm (kN/m^2)
Sandy clay	500	7.08	450
	1000	17.16	
	1500	34.16	
	2000	58.34	
	1800	47.9	
Dense sand	1800	9.8	1062
	5000	62.58	
	4000	44.31	
	4200	47.5	
	4250	49.3	
Medium dense sand Above Dense sand	1000	4.98	1188
	5750	66.4	
	5000	53.4	
	4500	45.6	
	4750	48.7	
Medium dense sand Above Soft clay	1500	127.9	200
	750	36.4	
	850	62	
	800	47.6	
Medium stiff clay Above Dense sand	1800	36	575
	2500	54.5	
	2300	48.4	

Table 5
Ultimate stress analysis of footing dimension (3 x 3) for different soil profile.

Soil Type	Load (kN)	Settlement (mm)	Ultimate Stress under allowable settlement of 50 mm (kN/m^2)
Sandy Clay	2000	19.9	390
	3000	37.2	
	4000	62.4	
	5000	94.1	
	3500	49	
Dense Sand	4250	24.6	1020
	9000	46.9	
	8000	40.1	
	8500	43.5	
	9200	48.3	
Medium dense sand Above Dense sand	9000	46	1000
Medium dense sand Above Soft clay	1500	56	160
	1350	40	
	1450	47.3	
Medium stiff clay Above Dense sand	2500	18.6	510
	4250	41.8	
	4600	46.2	

4.2. Minimum required spacing between two adjacent footings

Numerical analysis indicates that the load bearing capacity of an individual footing may be affected by adjacent footing's location. A close interval of two footings reduces individual footing capacity under allowable settlement. At a certain distance the influence becomes insignificant. The minimum spacing at which two adjacent footing can be shown resistant equivalent to their individual capacity have been summarized in Table 6.

Table 6
Required minimum spacing for sandy soil.

Soil Type	Footing Dimension (m^2)	Max Allowable Stress (kN/m^2)	Settlement (Max 50 mm)	Min Required Spacing (m)
Sandy Clay	2 x 2	450	49	3
Dense Sand	2 x 2	1062	49.2	3
Medium Dense Sand Above Dense Sand	2 x 2	1187	46.5	3
Sandy Clay	3 x 3	390	48.4	3
Dense Sand	3 x 3	1020	45.2	3
Medium Dense Sand Above Dense Sand	3 x 3	1000	43	3

Table 7
Required minimum spacing for clayey soil.

Soil Type	Footing Dimension (m^2)	Max Allowable Stress (kN/m^2)	Settlement (Max 50 mm)	Min Required Spacing (m)
Medium Dense Sand Above Soft Clay	2 x 2	200	44.5	2
Medium Stiff Clay Above Dense Sand	2 x 2	575	48.5	2
Medium Stiff Clay Above Dense Sand	3 x 3	510	48.2	2

As shown in Table 6 and Table 7 it is obvious that minimum required spacing between two consecutive shallow footings for sandy type soil is 3m (Fig. 16) and for clayey type soil is 2m (Fig. 15). If the footings are placed less than 3m in sandy type soil and less than 2m in clayey type soil, then their influenced stress area overlaps. In that case smaller bearing capacity values should be considered or combined footing could be a good alternative in the perspective of foundation level.

It is also noticeable that footing dimension (2 x 2) and dimension (3 x 3) behave almost similarly. For both the cases minimum required spacing remains same. Which indicates footing dimension may have no effects on required minimum spacing for not overlapping influenced stress area between two adjacent footings.

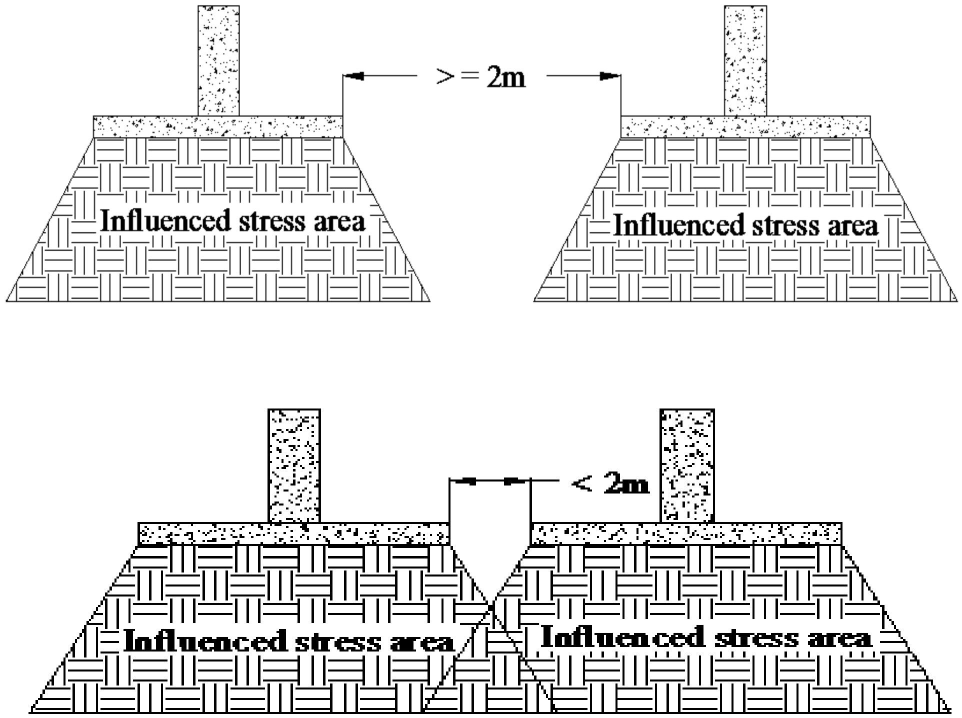


Fig. 15. Influenced stress area on clayey soil after application of load on footing.

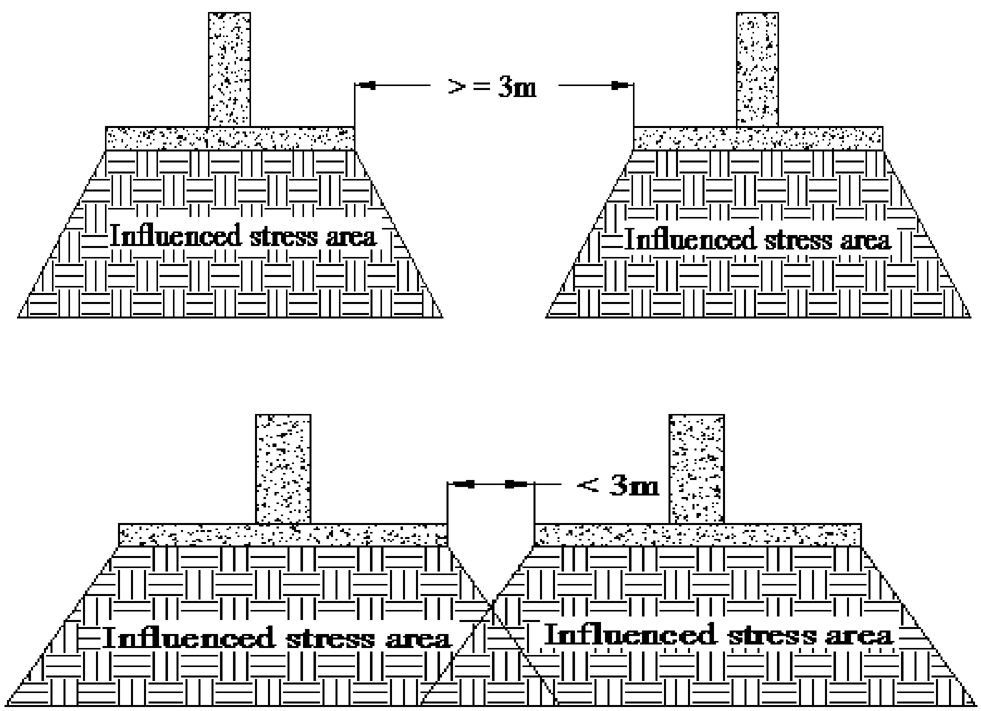


Fig. 16. Influenced stress area on sandy soil after application of load on footing.

4.3. Shallow footing behavior under allowable settlement (50 mm)

As the procedure mentioned in Methodology for numerical analysis, settlements of footing are calculated for different stress conditions by using PLAXIS 3D FOUNDATION for different footing dimensions. During this process spacing between two consecutive footings were kept 1.5 meter for different dimensions. Finally, the outcomes are represented as Stress vs Settlement graph (Fig. 17).

This work has been repeated by keeping 2 meter (Fig. 18) & 2.5 meter (Fig. 19) spacing between two adjacent footings to observe shallow footings behavior under allowable settlement of 50mm.

Following the same outcomes Stress vs Dimension graph (Fig. 20) and Stress vs Distance graph (Fig. 21) are also plotted to show the behavior of shallow footing under allowable settlement.

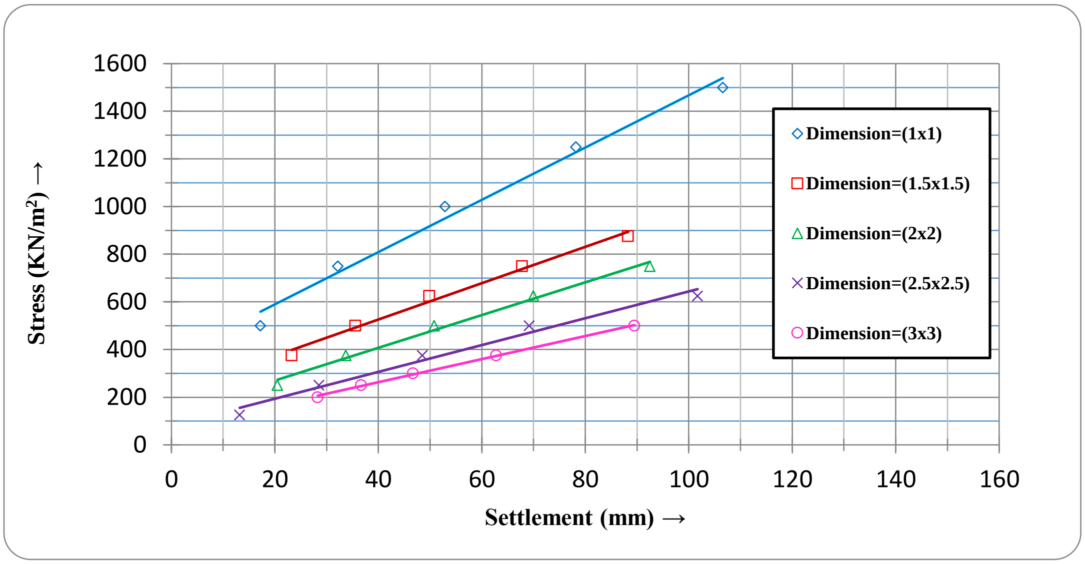


Fig. 17. Stress vs. Settlement graph for different footing sizes (spacing 1.5 m fixed between two adjacent footings).

Table 8
Regression analysis of Stress vs Settlement (spacing 1.5 m fixed between two adjacent footings).

Footing Dimension (m^2)	Regression Equation	Regression value, R2
1 x 1	y=10.96x+370.2	0.986
1.5 x 1.5	y=7.623x+221.1	0.989
2 x 2	y=6.867x+132.5	0.990
2.5 x 2.5	y=5.627x+81.13	0.980
3 x 3	y=4.840x+69.39	0.998

Fig. 17 represents the combined graph of Stress vs Settlement for 1.5 meter spacing between two adjacent footings. Each graph line represents stress capacity of different footing dimensions under allowable settlement of 50mm. The regression values of best fitted lines indicate a good representation which can be extended for larger values (Table 8). From Figure 8, it is very clear that as the footing size increases, the graph lines representing higher dimensions continue to dragging down below. It indicates as the footing size increases the stress capacity decreases.

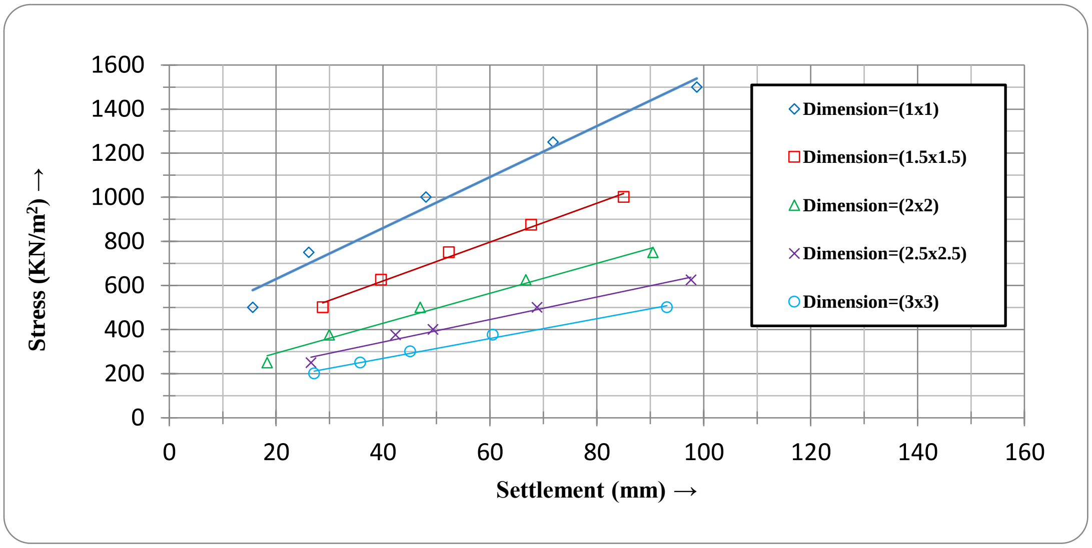


Fig. 18. Stress vs. Settlement graph for different footing size (spacing 2 m fixed between two adjacent footings).

Table 9
Regression analysis of Stress vs. Settlement (spacing 2 m fixed between two adjacent footings).

Footing Dimension (m^2)	Regression Equation	Regression value, R2
1 x 1	y=11.55x+398.6	0.979
1.5 x 1.5	y=8.807x+268.5	0.991
2 x 2	y=6.788x+157.4	0.984
2.5 x 2.5	y=5.102x+139.6	0.983
3 x 3	y=4.500x+89.63	0.992

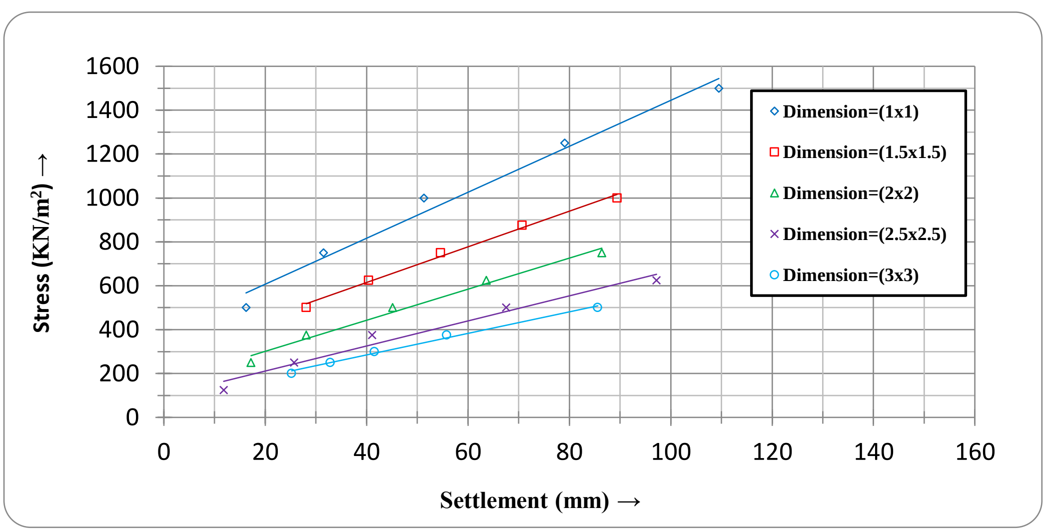


Fig. 19. Stress vs Settlement graph for different footing size (spacing 2.5 m fixed between two adjacent footings).

Table 10
Regression analysis of Stress vs Settlement (spacing 2.5 m fixed between two adjacent footings).

Footing Dimension (m^2)	Regression Equation	Regression value, R2
1 x 1	y=10.47x+397.6	0.981
1.5 x 1.5	y=8.121x+290	0.993
2 x 2	y=7.078x+159.6	0.984
2.5 x 2.5	y=5.710+97.14	0.971
3 x 3	y=4.905+88.67	0.991

Fig. 18 & Fig. 19 represents the repetition of Stress vs Settlement analysis for 2 meter and 2.5 meter spacing between two adjacent footings respectively. Similar to Fig. 17 each cases it is noticed that as the footing size increases, the graph lines representing higher dimensions continue to dragging down below by indicating as the footing size increases the stress capacity decreases.

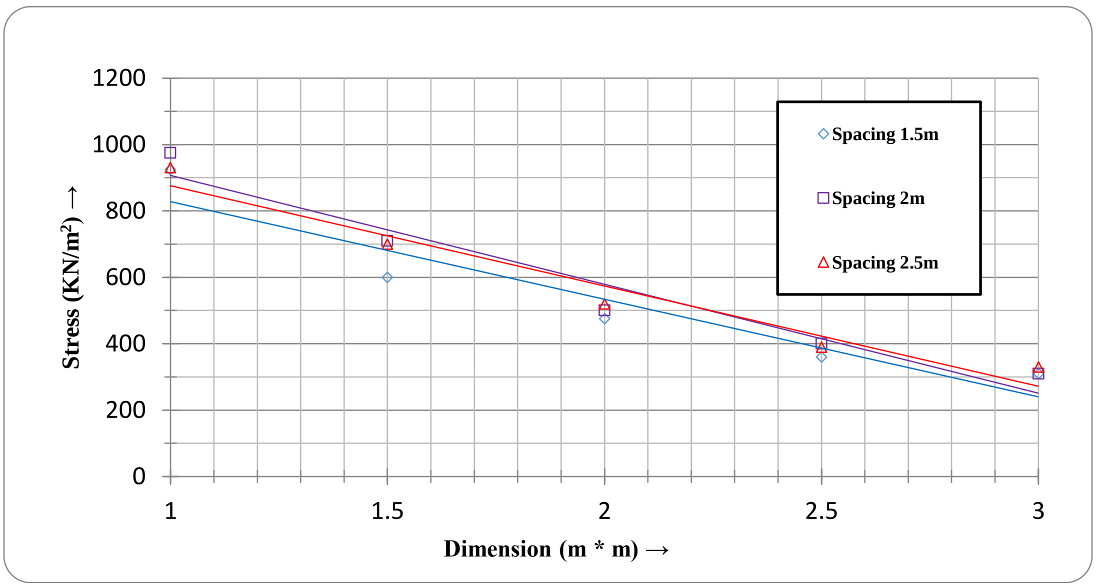


Fig. 20. Stress vs. Dimension graph for different spacing (settlement 50 mm fixed).

Fig. 20 represents the combined graph of Stress vs. Dimension for allowable settlement of 50mm. It is noticeable that the points of the curved lines representing different spacing in graph are located very close to each other. As shown in graph stress capacity varies for (1 x 1) footing 925-975 kN/m^2, for (1.5 x 1.5) footing 600-710 kN/m^2, for (2 x 2) footing 475-520 kN/m^2, for (2.5 x 2.5) footing 360-400 kN/m^2, for (3 x 3) footing 310-330 kN/m^2.

So spacing may have negligible effect on variation of footing sizes. And it is also noticeable that as the size of the footing increases stress bearing capacity decreases which was seen in earlier analyzation on Stress vs. Settlement. (Fig. 17, Fig. 18 & Fig. 19).

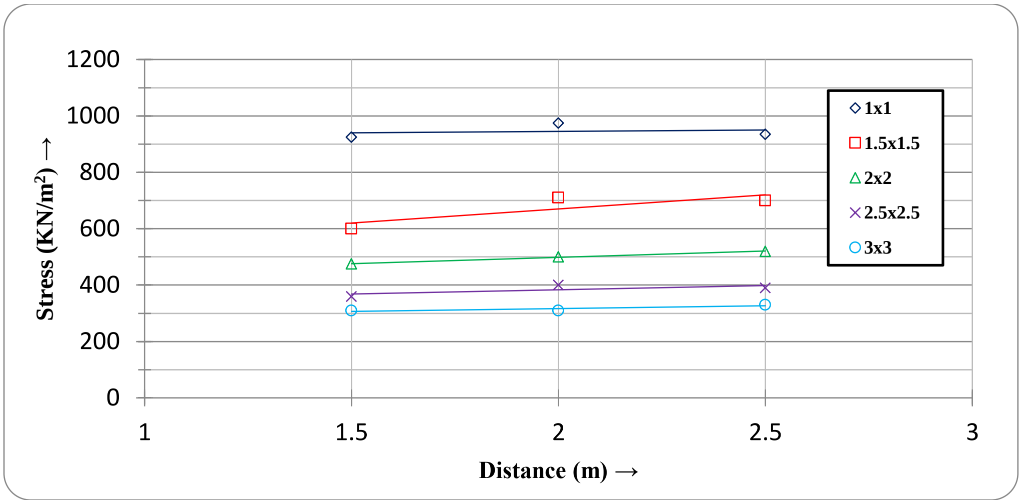


Fig. 21. Stress vs. Distance graph for different footing size (settlement 50 mm fixed).

Fig. 21 represents the combined graph of Stress vs. Distance under allowable settlement of 50mm for different dimensions. The graph lines representing different dimensions are found as flat indicating less stress deviation in varying spacing between two adjacent footings.

It is also observed that as the size of the footing increases stress bearing capacity under allowable settlement of soil decreases similarly found on Stress vs. Settlement (Fig. 17, Fig. 18 & Fig. 19) & Stress vs. Dimension analysis. (Fig. 20).

5. Conclusion

Using PLAXIS 3D FOUNDATION software different dimensions of footings have been analyzed in different conditions of layered soil for finding the generated stress capacity of footing under allowable settlement, isolated footing's influence area and to check them with conventional methods. And then executing analysis over those outcomes, other relevant findings have also been originated which are being conclusively recommended here.

Analyzing through all the test model results of these are the outcomes have been sorted out:

➢ The data of the Table 4 & Table 5 indicates that the presence of clayey soil in considerable depth shown significantly less bearing capacity under allowable settlement.

➢ Footing may act as an isolated footing in 3 m away from another footing on sandy soil as shown in Table 6. It is noticed that two adjacent footing's influenced stress area don't overlap if the footings are placed 3 meter apart on sandy soil.

➢ Footing may act as an isolated footing in 2 m away from another footing on clayey soil as shown in Table 7. It is noticed that two adjacent footing's influenced stress area don't overlap if the footings are placed 2 meter apart on clayey soil.

➢ Sizes of footing may have insignificant effect on spacing between two adjacent footings. As shown in (Fig. 22), stress capacity varies for (1 x 1) footing 925-975 kN/m^2, for (1.5 x 1.5) footing 600-710 kN/m^2, for (2 x 2) footing 475-520 kN/m^2, for (2.5 x 2.5) footing 360-400 kN/m^2, for (3 x 3) footing 310-330 kN/m^2 for different spacing between two adjacent footings. Similar studies have been noticed on (Fig. 23), where varying spacing has not any significant impact on generated stress on footing. So spacing may have negligible effect on variation of footing sizes.

Designers may find useful solutions to choose footing size in different soils considering stress bearing capacity, designers may also find economical solution in choosing isolated or combined footing in case of 2m or 3m gap for two adjacent footings based on soil type through this research.

In this research several parameters have been left unused and untouched i.e. effect of ground water, cutback problem, many other soil types etc. For making the results of this research more representative, reliable and precise, research on other parameter should be done in future. The recommended parameters which should be investigated in future are as follows:

- Perform numerical analysis under those soil samples which is collected from different field conditions.
- For estimating ground water effect on footing, Ground water level at various positions needs to be considered.
- Effect of cutback on shallow foundation need to perform. Because there are so many plumbing and gas line without proper planning which means any correction or check on that line need to cut near foundation area in future.

Conflicts of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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