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Bearing Capacity of Square Footing Resting on Layered Soil

Sarah Abdul Hussein Mandeel[a], Haider M. Mekkiyah[b], Abbas Fadhil Ibrahim Al-Ameri[c*]

[a]*M.Sc. Student, Department of Civil Engineering,University of Baghdad,, Baghdad, Iraq.*
[b]*Assistant Professor, Department of Civil Engineering,University of Baghdad,, Baghdad, Iraq.*
[c]*Lecturer, Department of Civil Engineering,University of Baghdad,, Baghdad, Iraq.*

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ABSTRACT

The bearing capacity of layered soil studies was carried out with various approaches such as experimental, theoretical, numerical, and combination of them. This work is focused on the settlement and bearing capacity of shallow foundations subjected to the vertical load placed on the surface of layered soils. The experimental part was performed by manufacturing soil cubic container (570 mm x 570 mm x 570 mm). A model square footing of width 60 mm was placed at the surface of the soil bed. The relative density of sand was constant at 60%, and the clay was prepared with a density of 19.2 (kN/m^3) and water content of 14.6%. PLAXIS 3D FEM was used to simulate the experimental tests and performing a parametric study. The results showed that there was a good agreement between experimental work and corresponding numerical results. The value of the bearing capacity was obtained from load-settlement curve. The bearing capacity of layered soil showed higher value for footing resting on clay over sand soil. It was found that an increase in the ultimate bearing capacity regarding the clay over sand with increasing in first layer thickness ratio; while, a decrease has been indicated for the sand over clay. The critical depth was found at H = (2-3m), and the failure pattern was not unique for layered soil.

1. Introduction

In geotechnical engineering, the major topic is a behaviour related to shallow foundations on the soil. The ultimate bearing capacity which is related to shallow footings was considered as challenging amongst the geotechnical engineers and researchers. The structure self-weight as well as the applied loading including wind load and live load, should be economically and safely transferred to the soil. The foundation's ultimate bearing capacity can be well-defined as the load where the shear failure which is related to soil beneath the foundation happens Shoaei et al. [1].

So far, a lot of numerical and experimental researches were conducted for determining the bearing capacity regarding shallow foundation on the soils. The majority of bearing calculations of the shallow footings were assessed with the use of a conventional theory where the bearing capacity factors have been used. Also, the elasticity theory has been carried out in analysis in which the soil was indicated for being rigid, homogeneous, and isotropic for simplifications in the geotechnical engineering practices. Yet, the soils are of different stratums in the earth, they are not homogeneous in nature. At many places, there exists multi-layered soil with different depths and have different soil properties Nujid et al. [2].

* *Corresponding author:*
E-mail address: alameri.abbas@gmail.com (Abbas Fadhil Ibrahim Al-Ameri)

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Nomenclature

B	width of footing (m)		*Greek symbols*	
C	Cohesion of soil (kN m^{-2})		Ψ	Dilatancy angle
cc	Coefficient of curvature		$\gamma_{d(\max)}$	Maximum dry unit weight of sand (kN m^{-3})
cu	Coefficient of uniformity		$\gamma_{d(\min)}$	Minimum dry unit weight of sand (kN m^{-3})
D10	The size at 10% finer by weight (mm)		$\emptyset$	Angle of internal friction (degrees)
D30	The size at 30% finer by weight (mm)		γ	Unit weight of soil (kN m^{-3})
D60	The size at 60% finer by weight (mm)		v	Poisson's ratio
Dr	Relative density of sand			
E	Young modulus (kN m^{-2})		*Subscripts*	
H	Thickness of top soil layer (m)		FEM	Finite element method
H/B	Ratio (thickness of soil layer to the width of footing)			
Nɣ	Bearing capacity factor			
S/B	Settlement to the footing width ratio			

The failure mechanism related to the layered soil is on the basis of thickness as well as soil properties of all layers. In a few cases in which the top layer was fairly thick and consisted of the weak soil, the mechanism of the failure might be limited in the top layer, while the strength regarding the rest lower layers won't have an impact. However, in various other cases, the failure mechanism might include at least two layers Zhu et al. [3].

A lot of significant examples exist for the tasks of the foundation engineering where it might be of high importance to involve the impact of soil layers when assessing the bearing capacity. For example, the raft foundations and shallow offshore foundations, typically have large physical dimensions; therefore, the potential failure surfaces might be extending to the considerable distance below the surface of the soil. Also, it is indicated that any of the soil layers in such failure surface depths can be affected via failure load. Other examples consist of the structures that are placed on the engineered fill layers is a storage oil tank, as well as un-paved roads that are built on the soft clay in which the layer of a compacted fill will be applied for spreading the load applied by passing vehicles Ramadan et al. [4].

In this research, lab tests have been performed and finite element simulations of these tests using the finite element program PLAXIS 3-D were conducted for investigating the ultimate bearing capacity in addition to the settlement and mode of failure layered soil under a vertical central load.

1. Previous Research

1.1 Experimental Research

Carlos et al. [5] used new punching shear failure according to the project area approach that has higher similarity to the actual failure shape. He created a bearing capacity equation with regard to strip footing on the basis of 2-layered soil as a function related to the characteristics of lower and upper soil layers, upper layer's thickness, footing's depth/width ratio as well as the failure surface angle in terms of vertical. The suggested equation was designed via the summation of forces induced in addition to being mobilized against the exerted pressure at the chosen strip element that is located in the upper layer of the sand. Furthermore, there was wide disagreement for high (H/B) ratio values and good agreement for the small (H/B) ratio values.

Huang and Qin [6] were estimated the bearing capacity for strip footings based on two-layered soil. The failure mechanism is shown in **Fig. 1**.

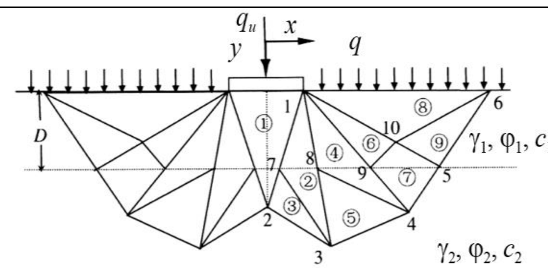


Figure 1: The suggested Huang and Qin (2009) failure mechanism.

The process of the analysis which has been developed by Huang and Qin [6] consists of two fundamental sub processes called compatible velocity field determination and critical failure determination, through which the bearing capacity has been achieved. Results for the 2- layered soil sand on clay profile will be compared with the ones of Hanna and Meyerhof [7] and it has been noticed that through the increase of the thickness of the top layer, the discrepancy rises via overestimating Huang's approach.

Ornek, et. al. [8] performed field test with the use of 7 separate footing diameters up to 0.9 m, in addition to 3 different thickness of the granular fill layers. As the tests have ended, the load–settlement curves were plotted, while the bearing capacity that is related to the circular shallow footings which are supported via compacted granular fill layers over a natural clay soil has been predicted. The work results indicated that there is an increase in the bearing capacity as the foundation size increases and using granular fill layers over the natural clay soil has a significant impact on settlement characteristics and bearing capacity. Furthermore, there has been an increase in bearing capacity ratio (BCR) when the granular fill thickness increased for all the footing diameters.

Ramadan and Hussien [4] investigated the behaviour of footing under vertical load on 2-layered soil. The work was carried out for bearing capacity which is related to sand overlying clay, numerical and experimental works were also conducted. The results were presented for the load-settlement curves, the ultimate bearing capacity. Moreover, non-dimensional relationship for the effect of the upper layer thickness to the ratio of footing width, (H/B), was presented in addition to the strength related to the upper layer soil on bearing capacity. Also, the failure modes of the foundation soil system were provided. It has been indicated that ultimate bearing capacity regarding dense sand over medium clay is increased with an increase of footing width (B) and ratio of sand thickness, (H/B), whereas decreasing for the loose sand over medium clay. In addition, there is an increase in sand ultimate bearing capacity over clay with increasing upper sand relative density. The failure pattern is showing punching shear failure in upper dense sand and the local shear failure in lower clay with regard to H/B = 1. The general shear failure has been indicated at H/B = 3 and also for the sand bed. Furthermore, in upper loose sand at H/B = 1 general shear failure has been indicated that is modified to local shear failures when H/B = 3.

Misir and Laman [9] investigated the bearing capacity related to the circular footings on the granular fill layer which is over the soft clay soil. The bearing capacity has been assessed with the use of empirical estimation approach on the basis of physical modelling on-site and in the laboratory. The statistical analysis was conducted in the case when experimental cases have been complicated and when there are very high costs to construct and monitor full-scale test reservoirs. In addition, from field and laboratory test results, it has been indicated that bearing capacity regarding circular footings on a granular filling layer over the soft clay soil has been increasing up to 78% depending on granular filling layer thickness with regard to various footing diameters. On the basis of comparisons of such formulations as well as field plate load tests, also laboratory results from this work, the results were in good accordance with predicting the convergence's behaviour via various works in the researches.

1.2 Finite Element Research

Zhu [3] presented the ultimate bearing capacity associated with rough strip footings which rest on two layers of clay soil as well as subsequent cohesion coefficient (Nc). The computations have been achieved via commercial FEM software (ABAQUS). The results were put in comparison with the published limit analysis and showed excellent agreement. From the result, it has been indicated that in the case where a weak clay layer was overlaying strong one Nc will be increased with an increase of (H/B). Moreover, the magnitude related to Nc was verified for approaching 5.146 with regard to all the cases of weak clay on a strong one which is coinciding with the presumptions of failure surface which is limited to the top layer. Furthermore, the critical depth has been specified as the depth for which Nc approach 5.146 which is related to (H/B) = 2.

Moayed, et al. [10] presented the bearing capacity regarding ring footings on two layered soil using finite element software, ABAQUS. The upper layer was soft clay, while the lower layer has been cohesion less sand. In addition, Mohr-Coulomb plastic yield criterion has been utilized for soil modelling. The effect of the thickness of the clay layers were analyzed. From the result, it is found that bearing capacity is gradually decreased with the increase in clay layer's thickness. Also, with the increase in clay layer, the displacement vectors will propagate in the clay layer and nearly not entering the sand region, and with the decrease of clay layer, the displacement vector was limited in the clay layer.

Mosadegh and Nikraz [11] used the FEM approach for calculating the ultimate bearing capacity that is related to a strip foundation on one-layer and two-layer (clay over sand) of soil. The computations have been conducted with the use of ABAQUS (FEM software) for assessing the impact of soil parameters including initial condition, footing roughness, and dilation angel on the soil behaviour. The elastoplastic Drucker-Prager model is represented the soil behaviour, while the footing material was assumed for being isotropic as well as linear elastic. For a homogeneous soil profile, it is found that the wider and deeper failure mechanism is accumulated under footing with increasing dilation angel. The bearing capacity of the single-layer sandy soil acquired via ABAQUS is putted to comparison to the acquired via the Terzaghi equation. It was indicated that the bearing capacity values with regard to dilation angel for FEM analysis is 13% higher than the ones without dilation and. In addition, the bearing capacity obtained by Terzaghi has a value among those obtained by FEM.

Reddy and Kumar [12] presented the behavior of foundation resting on layered soils under vertical loading conditions. The different failure modes and the foundation deformation patterns have been specified with utilizing a finite element modelling software (PLAXIS). Also, the parameters including the soil layer's thickness, cohesion, and friction angle were varied for the purpose of studying their impact on failure pattern. Different cases such as a clay layer over the sand layer, sand layer over clay layer, and two clay layers with various cohesion values have been assessed through varying the overlying stratum thickness. For each case, the failure patterns are explained. From the result, it is found that when increasing the first layer thickness, the failure pattern related to layered soil will be totally different. In addition, the behavior of the failure pattern when clay overlay sand was significantly different from a vice versa case. Furthermore, the cohesion as well as the angle of friction value of the soil also found for altering the failure pattern.

2. Experimental Tests and Materials Used

The function to achieve the physical model is studying certain features related to the response of the prototype. In addition, the full-scale field tests on the foundations are considered as the best method to the verification and calibration regarding the analytical approaches for certain projects, however, the costs of such experimentations is high and the regulation of parameters of the soil and the evaluation of their impacts on the behavior of soil are difficult in addition to the difficulties related to loading full-scale prototypes until failure. Attain small scale laboratory models is considered as another choice. Providing the confidence of their validity is the significant aim of a small scale in the experimental models. The scaling effect should be reduced for satisfying the behavior observations at a small scale and the way it might be extrapolating for predicting the behavior of full-scale Al-Ameri [13].

2.1 The Clay Used in This Study

The clay soil utilized in the presented work was brought from Al-Nahrawan which is a city located 35 km east Baghdad, near brick quarries and from a depth of (1.0-1.5) m. The soil samples were collected from small bit as disturbed samples and placed in bags then transferred to the soil mechanics laboratory. The standard tests have been carried out for determining the soil's geotechnical properties. Following carrying out the needed conventional as well as other needed laboratory tests (compaction, plastic and liquid limit, hydrometer and sieve, unit weight, and triaxial test), the soil has been prepared for the model tests. The soil was specified as low-plasticity clay, CL, based on the unified soil classification system (USCS). Furthermore, the values related to the plasticity index, liquid limit, and plastics limit of clay have been acquired as 17.4%, 32.6%, and 15.2%, respectively, while the value related to a specific gravity of the clay soil is indicated to be 2.71. The undrained shear strength value of clay soil was 70 kPa as well as the internal friction's angle was 6° in dry condition. The dry unit weight in addition to the moisture content have been used as 19.2 kN/m^3, 14.6%, respectively.

2.2 The Sand Used in This Study

The sand soil used in the experimental studies was obtained from Karbala city. Laboratory tests (direct shear, unit weight, and sieve) have been carried out for this soil. All of the conventional test results have been provided in **Table 1**. According to the sieve analysis and USCS, the sandy soil is classified as poor graded sand (SP).

Table 1: Physical and mechanical properties of the soils used

Physical Property	Result
Sandy soil	
USCS-Soil Type	SP
D_{10} (mm)	0.25
D_{30} (mm)	0.41
D_{60} (mm)	0.81
Cc	0.83
Cu	3.24
γ_{dmax} (kN/m^3)	18.0
γ_{dmin} (kN/m^3)	15.0
G_s	2.71
Φ (°)	36.0
c (kN/m^2)	0.2
Clayey soil	
USCS-Soil Type	CL
G_s	2.71
LL, %	32.6
PL, %	15.2
Sand (0.075-4.75 mm) %	14
Silt (0.005-0.075 mm) %	35
Clay (< 0.005 mm) %	51

2.3 Preparation of Soil Layers

Before preparing the soil bed, trial tests have been conducted for controlling the effectiveness related to the preparation method. The glass container has been marked in 6 sections with a height of (9 cm) for each as can be seen in **Fig. 2**, and with the known value related to dry unit weight that has been needed in this work, the dry soil's weight might be specified for each one of the layers.

Figure 2. Preparation of soil layered within the glass box.

A steel tamping hammer has been utilized for compacting the soil through uniformly distributed blows for getting the needed density. For preparing the medium state sand layer with relative density (60%) which is utilized in this work, the sand has been poured in a box from a specific height and then tamping lightly. Also, a hygroscopic water content (≈ 0.5-3%) has been added to the sand before compaction and pouring for ensuring small cementation of the soil prior to tests Das [14]. On the other hand, the clayey soil was prepared at a dry unit weight of (19.20 kN/m^3) and with a corresponding (14.6%) water content to get undrained shear strength (c = 70 kPa). The natural clay was left for air-drying and pulverized by a hammer to small sizes. The dry clay was divided into groups; each group of known weight was mixed with water and kneaded by hand well. After mixing with water, the soil lumps were expelled out of the container and tamped with a steel hammer. The procedure continued until the required thickness of the bed was achieved.

2.4 Container Box and Testing Procedure

A cubic test box having 570 x 570 mm in plan and 570 mm in depth is utilized in experimental tests. The test box has been made of glass, with (15mm) as wall thickness. The aim of using glass is to allow better observation of soil homogeneity also a reference marker was used in the front side of the tank to help with the formation of the required layered model.

In each model test, the test container was placed on the steel base of the compression machine and the soil bed was prepared as per in section 3.3. After filling the container with a controlled density soil, the rigid square steel base plate with dimensions of 60 x 60 x 10 mm has been placed on the surface related to soil bed at the centre of the model. A small spherical hole was made by carving the centre of the footing surface to ensure transferring the vertical load to the centre regarding the foundation with a steel ball.

After that, the footing was loaded by the compression machine with a digital control system until the failure occurred. The loading process was controlled by the strain control technique and the loading rate was 1.0 mm/min. The load has been read from a digital weighing indicator that is connected to the load cell as can be seen in **Fig. 3**.

The average vertical settlement has been measured using a dial gauge with 0.01mm accuracy and a 30 mm stroke attached vertically on the surface of the footing. A magnetic holder was used to fix the dial gauge on the loading frame. **Fig. 3** shows the experimental setup which has been utilized for performing the tests.

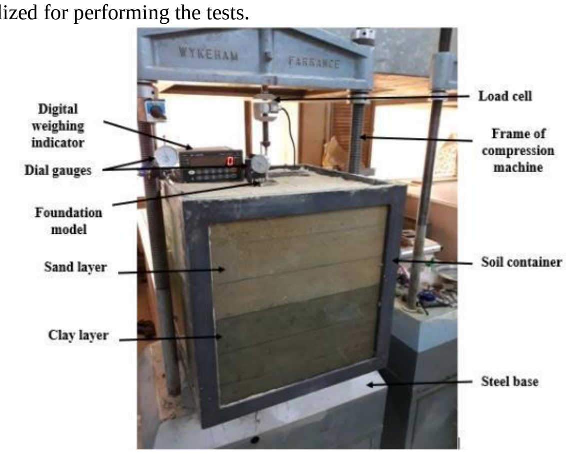


Figure 3. The experimental setup used to perform the tests.

3. Test Variables

The total number of conducted tests is 10 models. There are two main parts in the testing program, the first one is concerned with one-layer models (homogenous) with regard to clayey and sandy soil with the total number of tests of two, while the other one is concerned with a two-layer model (non-homogenous) of soil with a total number of tests of eight models. Four of these were performed in clay over the sand model, and the other ones are concerned with sand over the clay model. The thickness of the first layer was varied from H/B = 1 to H/B = 6 (H/B = 1, 2, 3, 6). Some of the testing setup of soil models is given in **Fig. 4**.

Figure 4: Some of the tests of soil models.

4. Finite Element Simulation

The experimental and numerical studies are considered in this study to accomplished each other in the field of geotechnical engineering. Finite element modelling has more advantages than experimental modelling for foundation analysis due to the parameters that may be easily varied and the details related to stresses as well as deformations throughout the system might be examined, in addition to the overall cost effective of such analyses. However, a 3-D finite element simulation for the experimental tests, utilizing PLAXIS 3D program, has been carried out for examining the actual behavior of the layered soil system. Actually, this step is regarded as a first step of the researchers' goals to make an intensive full-scale parametric study.

4.1 Geometry and Meshing

Firstly, a geometric model of dimension is created. The same internal dimensions that are related to the model box of laboratory tests have been utilized in numerical work for the purpose of simulating similar boundary condition, therefore the model dimensions have been (570 mm × 570 mm × 570 mm) defined via single borehole at the model's first corner. The borehole was defined as a location in model which have information related to the soil profile. In addition, the hydraulic head was under soil profile due to the fact that the water condition was not considered in the model. The loading is carried by a rigid surface plate square footing of (60mm × 60mm). A fine mesh is generated in the geometry. The model geometry and meshing are shown in **Fig. 5**. A point prescribed displacement is created at the centre of the footing to same settlement obtained from experimental work. The calculations were continued until the prescribed displacement of the soil reach to 20% of the footing width. Furthermore, the load- settlement curve acquired from output provided settlement of footing and ultimate bearing capacity. The same procedure is adopted for all models.

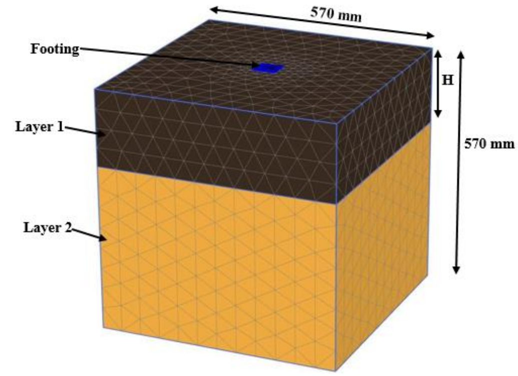


Figure 5: The model geometry and meshing for two-layered soil.

4.2 Modeling and Parameters

The footing has been modelled as a linear elastic material, while the soil is modelled in the Moher-Coulomb model. Material models and the input parameters of the FEM program are shown in **Table 2**.

In the finite element method, the displacement control approach is utilized to evaluate the load-settlement curve. In this approach, the load required to reach the desired displacement can be determined. The loading was stopped after settlement = 20% of the footing width, (S/B = 20%).

Table 2. Input parameters for the FEM program

Parameter	Sand	Clay	Footing
Material model	Mohr-Coulomb	Mohr-Coulomb	Linear Elastic
Material behaviour	Drained	Undrained (A)	Non-porous
Unit weight, γ, kN/m3	16.67	19.2	77.03
Young's modulus, E, kN/m2	30000	10000	193*106
Poisson's ratio, ν	0.30	0.35	0.15
Cohesion, c, kN/m2	0.2	70	___
Friction angle, Ø	36	6	___
Dilatancy angle, Ψ	6	0	0

5. Results and Discussions of Experimental Tests and FEM Simulation

It is well known that a wide range of the results can be obtained from the PLAXIS-3D 2013 software, but the output was limited to what needed for the comparison with experimental tests. The load-settlement relationships of the footing were obtained from loading tests of both experimental and FEM work and provided in **Fig. 6, 7**, **and 8**. The value related to the soil's ultimate bearing capacity from load-settlement curve defined according to (0.1B) is shown in **Table 3** for the illustration of the comparison between the experimental and FEM results. It can be seen that both of the experimental work and FEM modelling give almost the same behaviour.

There are two tests on homogeneous soils (clay having c = 70 kPa and sand with Dr= 60%), were performed. **Fig. 6** is providing the load-settlement responses related to the homogeneous foundations. Generally, the homogeneous beds showed nonlinear load-settlement variations.

A comparison between the theoretical bearing capacities those estimated with the use of general bearing capacity equation (q_u=c N_c F_{cs} F_{cd} F_{ci} +q N_q F_{qs} F_{qd} F_{qi} + 0.5 B ɣ $N_ɣ$ $F_{ɣs}$ $F_{ɣd}$ $F_{ɣi}$) Balla [15] with bearing capacities acquired from the experiment tests was carried out. It can be indicated that the ultimate bearing capacities for clay was (597 kPa) and for sand was (16.8 kPa), as is evident, the sand's bearing capacity obtained from experimental work is much higher than its value extracted by the equation.

The bearing-capacity model tests that are related to the shallow footings conducted in different geotechnical laboratories specified that the test results of the model on granular soil were generally high in comparison to those estimated via conventional approaches [16], [17], [18], [19], [20], [21], [22], [23]. This happens due to a few reasons, the major one is the un-predictability related to $N\gamma$ as well as the scale effect related to model tests. Several studies compiled by (DeBeer, 1965) [24] about the bearing capacity test results have been illustrated in **Fig. 9** as plot of $N\gamma$ versus γB. Also, as γB increased, the value of $N\gamma$ will be quickly decreased.

The layered foundations consisted of clay of different thicknesses (H=1B-2B-3B-6B) overlying sand and vice versa. Eight tests on two layeres of soil were performed. It might be indicated that the homogeneous clay bed showed a stiff load–settlement response in comparison to the sand bed. Thus, the layered foundations which have clay beds of C = 70kPa at the top surface, might be considered as stiffer soil overlain the softer soil; and vice-versa in case of sand over clay. This result is in good agreements with observations of Biswas & Krishna (2017) PLAXIS Manual [25]for foundations with softer layer overlying stiffer layer.

In **Fig. 7**, the load – settlement responses related to sand over clay foundations were provided. From the numerical and experimental observations (for softer soil which overlies through stiffer soil), the maximum bearing capacity has been indicated by approximately 70.9 kPa for H = 1B at S/B = 10%. With regard to H ≥ 3B, the bearing capacity was very much similar, with bearing capacity regarding homogeneous sand where it was approximately 54 kPa (in spite of the layer thickness variations, H/B). High bearing capacity related to H = 1B is due to the impact of more support for the sand layer obtained from underlying stiff clay. Generally, for sand layer of small thickness (H ≤ 3B), the failure surface will be extending to the lower layer; while, for thick layers (H > 3B), the failure surface will completely develop in top layer.

Fig. 8 shows the load–settlement curve of the clay over sand foundations. In these cases, the load-settlement responses have shown an increase in bearing capacity for the layer of clay overlying sand; where the large effect is indicated for stiff clay soil, regardless of variations in clay layer thickness (H).

The results for the two-layer soil shown in **Fig. 6 and 7** show that with increasing thickness ratio H/B, the bearing capacity of clay over sand increases, considering that bearing capacity of clay higher than that of sand whereas it decreases for sand over clay. When H/B ≥ 3 the lower soil doesn't affect the bearing capacity and the soil behaves as one layer of soil.

It is found that the failure pattern of layered soil is to be entirely different as the thickness of the first layer increases as shown in **Fig. 10**.

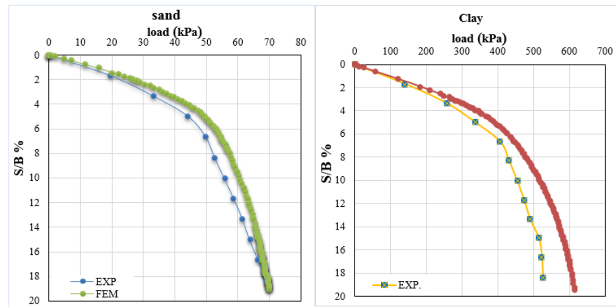


Figure 6. The experimental and numerical load-settlement curve of one layer of soil.

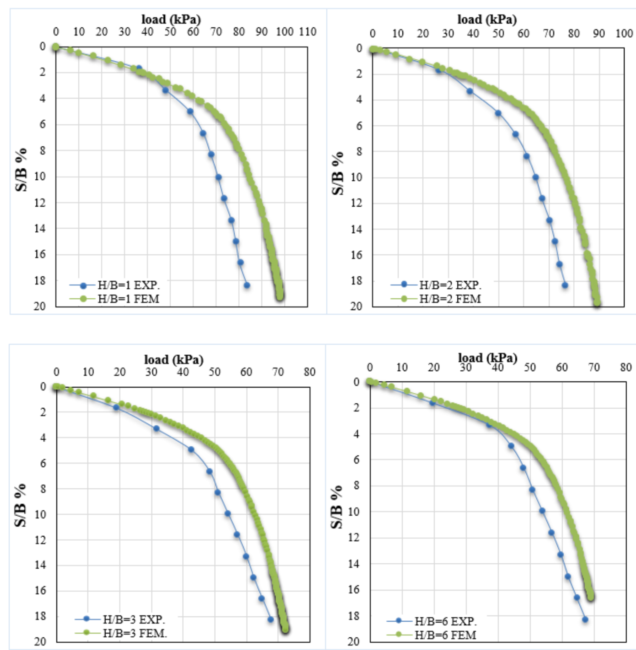
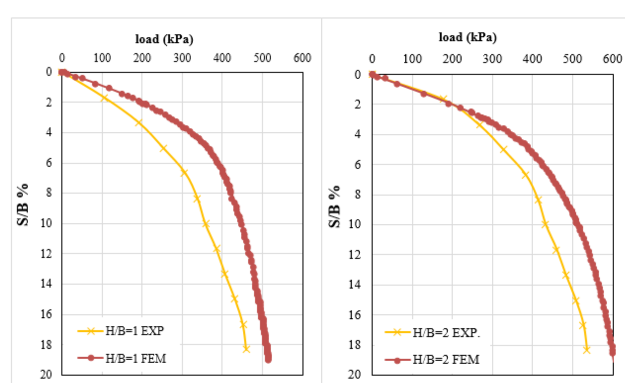


Figure 7. The experimental and numerical load-settlement curve of sand over clay layered.



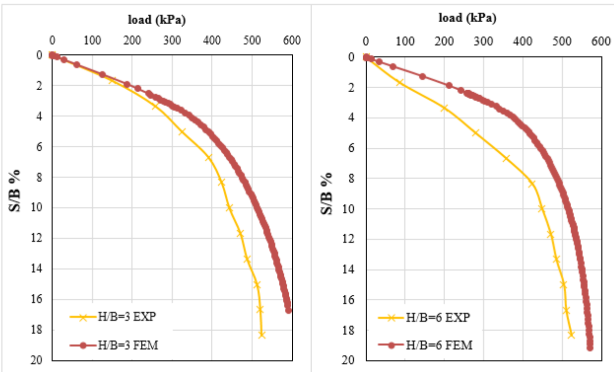


Figure 8. The experimental and numerical load-settlement curve of clay over sand layered

Table 3. Values of ultimate bearing capacity, Qu and the corresponding settlement ratio, S/B %.

Type of soil model	H/B	q_u (kPa) EXP.	q_u (kPa) FEM.
Sand	*	55.6	60.7
Clay	*	454.2	519.0
	1	70.9	84.8
	2	64.8	76.8
Sand over clay	3	54.2	63.0
	6	54.0	61.6
	1	357.3	447.0
	2	432.0	514.2
Clay over sand	3	443.2	515.0
	6	448.7	517.5

(*) one layer of soil

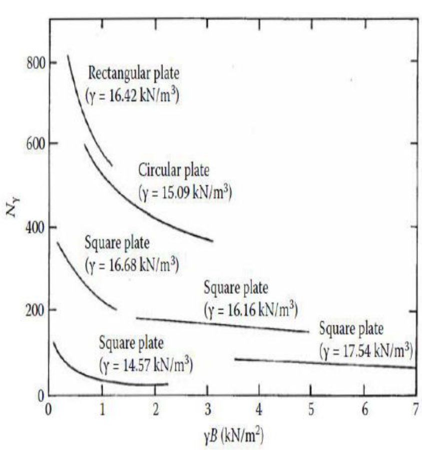


Figure 9. Variation of Nγ with γB (adapted after DeBeer, 1965)

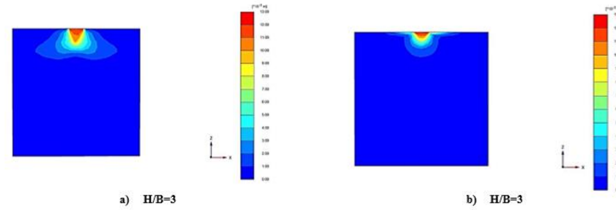


Figure 10. Failure pattern for the case of clay over-sand.

6. Conclusions

- For a layered foundation, the load-settlement responses showed higher bearing capacity values for stiffer subgrades.
- For this study, there was an increase in the ultimate bearing capacity of clay overlying sand with increasing clay thickness ratio, H/B; while, there was a decrease in cases of sand overlying clay with the increase in sand thickness ratio.
- The critical depth in this study, where the strength related to the bottom layer has no impact on the bearing capacity of the entire model is exist at H/B = (2-3).
- There is an excellent accordance between the experimental work as well as the corresponding numerical results using PLAXIS (3D) software, indicating that the numerical modelling used in this work for simulating the foundation behaviour on homogeneous and non-homogeneous soil is successful.
- The pattern of failure of the layered soil is completely different as the first layer's thickness increases. In addition, the behaviour of failure pattern when clay overlay sand was significantly different from a vice versa case.

REFERENCES

[1] M. D. Shoaei, A. Alkarni, J. Noorzaei, M. S. Jaafar and B. B. K. Huat, Review of Available Approaches for Ultimate Bearing Capacity of Two-Layered Soils, Journal of Civil Engineering and Management, 18(4), p. 469–482, (2012).

[2] M. M. Nujid and M. R. Taha, A Review of Bearing Capacity of Shallow Foundation on Clay Layered Soils Using Numerical Method, EJGE Journal, Vol. 19, pp. 811-824, (2014).

[3] M. Zhu, Bearing Capacity of Strip Footings on Two-Layer Clay Soil by Finite Element Method, in Proc. of the ABAQUS Users' Conference, Massachusetts, Boston, p. 776–787, June (2004).

[4] M. I. Ramadan and M. H. Hussien, Bearing Capacity of Sand Overlying Clay – Strip Footing, International Journal of Science and Research (IJSR), vol. 4, no. 11, pp. 1852-1859, (2015).

[5] A. F. Carlos, Ultimate Bearing Capacity of shallow Foundations on Layered Soils, MSc Thesis, Civil and environmental Engineering. Quebec: Concordia, (2004).

[6] M. Huang and H.-L. Qin, Upper-Bound Multi-Rigid-Block Solutions for Bearing Capacity of Two-Layered Soils, Computers and Geotechnics, p. 525–529, (2009).

[7] M. Ornek, M. Laman, A. Demir and A. Yildizd, Prediction of Bearing Capacity of Circular Footings on Soft Clay Stabilized with Granular Soil, The Japanese Geotechnical Society. Production and hosting by Elsevier, pp. 69-80, (2012).

[8] G. Misir and M. Laman, A Modern Approach to Estimate the Bearing Capacity of Layered Soil, Periodica Polytechnica. Civil Engineering, p. 434–446, (2017).

[9] R. Z. Moayed, V. Rashidian and E. Izadi, Evaluation on Bearing Capacity of Ring Foundations on two-Layered Soil, World Academy of Science, Engineering and Technology, vol. 6, (2012).

[10] Mosadegh and Nikraz, Bearing Capacity Evaluation of Footing on a Layered-Soil using ABAQUS, Journal of Earth Science & Climatic Change, (2015).

[11] V. S. K. Reddy and D. T. K. Kumar, Behaviour of Foundation in Layered Soils, International Journal of Science and Research (IJSR), vol. Vol. 7, Issue 1, (2018).

[12] D. Wood, Geotechnical modeling, Abingdon, Oxfordshire, Spon Press, (2004).

[13] A. F. I. Al-Ameri, Transient and Steady State Response Analysis of Soil Foundation System Acted Upon by Vibration, PHD. Thesis, Civil Engineering Department, University of Baghdad, (2014).

[14] B. M. Das, Principles of Foundation Engineering, Seventh Edition, (1997).

[15] A. Balla, Bearing Capacity of Foundations, Journal of Soil Mechanics and Foundoundation Div., ASCE, pp. 13-34, (1962).

[16] D. M. Milovic, Comparison between the Calculated and Experimental Values of the Ultimate Bearing Capacity, Proc., 6th ICSMFE, Montreal, pp. 142-144, (1965).

[17] B. Zadroga, Bearing Capacity of Inclined Subsoil under a Foundation Loaded with Eccentric and Inclined Forces: Part 1-Method Review and Own Model Tests. Archive of Hydroengrg. 22(3/4), pp. 333-336, (1975).

[18] W. Cichy, E. Dembicki, W. Odrobinski, A. Tejchman and B. Zadroga, Bearing Capacity of Subsoil under Shallow Foundations: Study and Model Tests, Scientific Books of Gdansk Technical University, Civil Engineering, pp. 1-214, (1978).

[19] A. Bolt, Bearing Capacity of a Homogeneous Subsoil under Rigid Footing Foundation Loaded with Inclined and Eccentric Force, In~ynieria Morska, 3(2), pp. 108-110, (1982).

[20] T. S. Ingra and G. B. Baecher, Uncertainty in Bearing Capacity of Sands, J. Geotech. Eng., ASCE, vol. 109(7), pp. 899-914, (1983).

[21] S. Shiraishi, Variation in Bearing Capacity Factors of Dense Sand Assessed by Model Loading Tests, Soils and Found. Journal, vol. 30(1), pp. 17-26, (1990).

[22] J. Hartikainen and B. Zadroga, Bearing Capacity of Footings and Strip Foundations: Comparison of Model Test Results with Eurocode 7, Proc., of 13th ICSMFE, New Delhi, India, no. 2, pp. 457-460, (1994).

[23] E. E. DeBeer, Bearing Capacity and Settlement of Shallow Foundations on Sand, Proceedings, Symposium on Bearing Capacity and Settlement of Foundations, Duke University, pp. 15-33, (1965).

[24] A. Biswas and A. M. Krishna, Behaviour of Circular Footing Resting on Layered Foundation: Sand overlying Clay of Varying Strengths, International Journal of Geotechnical Engineering, pp. 1-16, (2017).

[25] PLAXIS Manual, (2013).