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STUDY IMMEDIATE AND CONSOLIDATION SETTLEMENT OF SHALLOW FOUNDATIONS

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Abstract

In the present study, laboratory model tests and numerical analysis are carried out to study the immediate, and consolidation settlement of shallow foundations rested on clayey soil. The purpose is to evaluate the immediate and consolidation settlement of different cases and compares them with the calculated values using theoretical equations; the numerical analysis is utilized by the Plaxis-3D program for developing the finite element model, whereas the soft soil model was used for simulation. It was studied the effect of three parameters on the behavior of the foundation for immediate and consolidation settlement, these parameters are soil cohesion, the pressure applied on the foundation, and layer thickness. The obtained results indicated that the simulation using the soft soil model underestimates the immediate settlement by about 30 % and gives excellent results for predicting consolidation settlement. The total settlement of shallow raft foundation rested on a clay layer of depth three times raft width to one time was increased by about 66 %. The consolidation settlement is much higher than the immediate in clayey soils, however, the average of immediate to consolidation settlement is equal to 0.3 % for pressure 20 kPa, and increases with rising applied pressure until it reaches 1.2 %. The numerical analysis revealed a lower value than the calculated using the theoretical equation for immediate settlement, while for consolidation settlement, the results are close except for the soft clay condition c_u = 20 kPa.

Keywords:

Immediate settlement;
Consolidation settlement;
Shallow foundation;
Soft soil model;
Clay.

1 Introduction

Undeniably designing the shallow foundations placed on compressible soil beds must satisfy two criteria, stability and deformation. For stability, it must be ensured that the load applied from foundations does not cause shear failure in soil, while the deformation requires that the developed total settlement should be within acceptable limits that can be tolerated by superstructure type. Usually, the settlement of a foundation is divided into three types; immediate, consolidation, and creep, and estimation of its value is done through theoretical equations based on some assumptions. However, these methods cannot give accurate results to the real settlement due to the complex relationship between the foundation and the soil and the nature of the soil components.

Tang Bin et al. [1] used a finite element program to analyze of the consolidation settlement of foundations in soft soil according to rheological characteristics

Mimura et al. [2] studied the consolidation settlement of a runway in Kansai International Airport .They compared the local actual monitoring value after construction with the numerical value of the finite element. They found that the two results are almost similar.

Similarly, Ba et al. [3] examined the effect of the size, foundation stiffness, and the load applied on raft foundations on the compressed zone thickness and the settlement generated, their findings indicated that the foundation settlement considerably increased with increment of the foundation size and the load applied, so that. They also found a good agreement between simulated settlement by Plaxis-2D program to the observed settlement of a case study.

Akpila and Omunguye [4] performed laboratory tests and analyses to study the influence of foundation settlement on the adoption of an appropriate applied pressure of a shallow footing found on sandy clay soil. In general, the allowable load capacity of footing changes from 73 - 86 kN/m^2 for raft width equal 19.3 to 29.5 m up to 3 m levels below ground surface, it was observed that settlement consideration affect the value of bearing capacity needed for the foundation analysis and design in a sandy clay soil. Furthermore, the total settlement decreased with increasing the foundation size and depth, indicating that the raft foundations under an applied pressure of 50 kPa satisfied the bearing capacity and settlement criteria, which is lower than the evaluated bearing capacity.

Salahudeen and Sadeeq [5] investigated the capacity bearing and settlement of foundation at Minna City Centre. The evaluation of foundation bearing capacity and settlement values for preliminary geotechnical design of foundations was performed using some conventional empirical (analytical) methods, while the numerical analysis using Plaxis 2D. The results obtained showed that the numerical analysis used for estimating the allowable bearing capacity of the shallow foundation and settlement provides acceptable results.

Muntau and Bathaeian [6] explored the settlements and bearing capacity of shallow foundations rested on sand and clay soil and investigated the development of shear zones and load-settlement behaviour, their results revealed that the analytical approaches produced a very simplified solution for bearing capacity and failure pattern of shallow foundations as the compaction and deformations of the underlying soil were not taken into account.

Arab et al. [7] performed a numerical simulation for evaluating the elastic settlement of shallow foundations resting on soft clayey soil, The main objective of their study was to assess the variation in the water table and the depth of the footing on the settlement value and to determine the optimal size of footing that withstands excessive settlement, they observed that as the area of footing increased, the settlement decreased, and the footing depth significantly affect the settlement value.

It can be inferred from the above that, there are number of studies related to the assessment of the foundation settlement. However the consolidation settlement requires a long time up to many years which needs a special tool for monitoring the excess pore water pressure, this could be the main reason for limited research to study this type of settlement in clay soils. Therefore, we devoted this study to augment this incommensurate part by evaluating the immediate and consolidation settlement of different cases using the finite element method and comparing them with the estimated values using theoretical equations. Moreover, to investigate the effect of some parameters on the behavior of the foundation.

2 Experimental test

In order to quantify the immediate and consolidation settlement of the foundation, an experimental test of model footing under increased load is performed. This can help in validation of the finite element program and to simulate full-scale cases to measure the settlement. First, a constant load is applied, and the settlement is observed with time; a piezometer was used during the test and placed inside the clay to observe the consolidation process. The test is continued until the completion of about 90 % of the consolidation by observation of the reading of the piezometer during the test. A square foundation of steel plate with 3 mm thickness and 210 mm width was used. The test assembly consists of a steel tank and a mainframe. The tank was of 800 mm long, 800 mm width, and 600 mm height, and the soil depth was equal to 450 mm. The mainframe consists of two vertical columns and one horizontal beam. The load is applied using a level arm ratio of 1:3 that consist of a steel beam of adequate flexural strength to transfer the vertical load, as shown in Fig. 1.

Footing settlement was measured using two dial gauges of 25 mm capacity with graduations of 0.001 mm. A data acquisition system and laptop computer are used to record the reading of the piezometer during the test. The physical properties of soil are given in Table 1, and the results of the test can be seen in Fig. 2, 3. It can be seen from Fig. 3, that the efficiency of measuring the piezometer is approximately 60 %, this is due to several reasons, including the difficulty of operating it in clay soils, and the soil may not be fully saturated because it was remolded soil. It can be observed that a period of 6 days is sufficient for the completion of about 80 % of consolidation as the dissipation of excess pore water pressure in three directions and the fact that the soil is remolded.

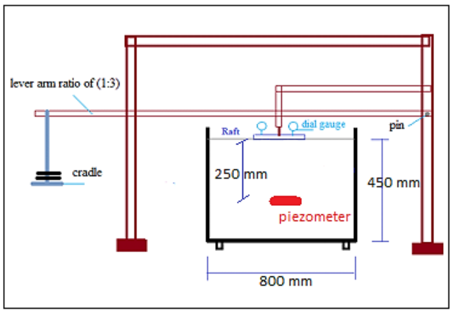

Fig. 1: Schematic diagram of the test assembly.

Table 1: Physical properties of clay soil used.

Property	Value	Specification
Liquid limit (L.L)	32	ASTM-D4318-2010
Plastic limit (P.L)	16	ASTM-D4318-2010
Plasticity index (P.I)	16	ASTM-D4318-2010
Specific gravity (Gs)	2.71	ASTM-D854-2010
Passing sieve No. 200 [%]	86	-
Soil classification	CL	-

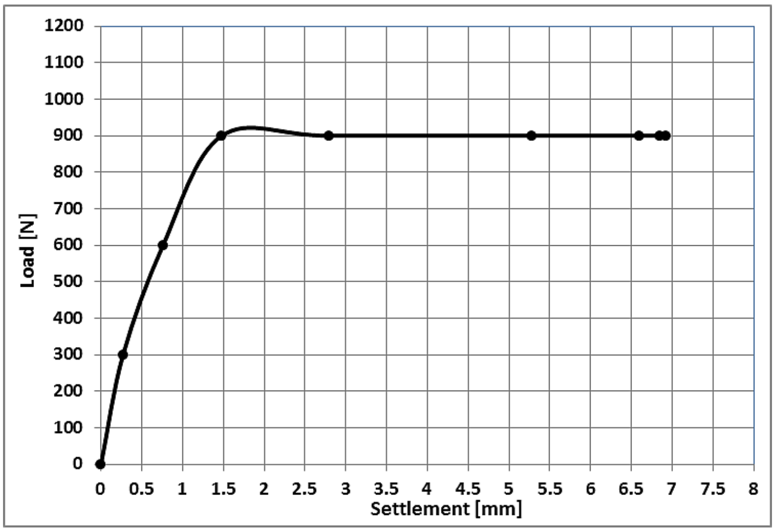

Fig. 2: Load-settlement curve of test.

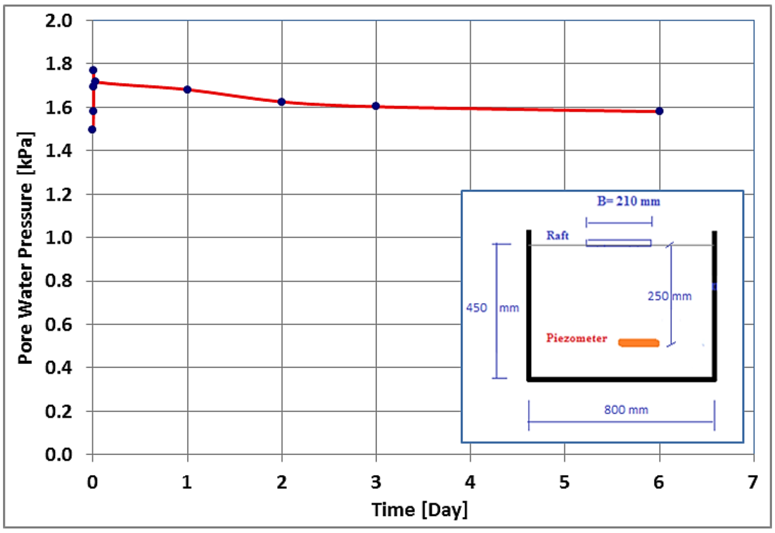

Fig. 3: Relation of pore water pressure with time for the test.

3 Validation of finite element program

The finite Element Method (FEM) is one of the popular numerical methods that are able to analyze a complex problem in various forms. According to the results of Bahloul [8], it can be concluded that Plaxis software predicted the real consolidation settlement after comparing the settlement observed in the field with that obtained by using Plaxis program, therefore, the finite element simulation is performed by the Plaxis program; a numerical investigation was carried out by a soft soil model to represent the load settlement and time settlement behavior of footing. The soft soil model is a Cam-Clay model that is utilized especially to study the primary compression of normally consolidated clay, so based on finite element analysis by this model found in the Plaxis program, the trends of ground settlement can be depicted accurately [9].

Validation is carried out to examine the efficiency of the program using this model for predicting the behavior of the experimental results. The parameters of soil used in the validation model are given in Table 2. The geometry of the model simulated by the program and the contour of vertical displacement of the validation case can be seen in Fig. 4 and 5, where the settlement is measured at a node in the center of the footing. In the comparison between numerical analysis and experimental results of the relations between applied pressure q versus settlement ratio (ratio of settlement S to the width of footing B), as shown in Fig. 6, it can be seen the program gave a percentage of theoretical to experimental results about 30 % concerning immediate settlement this means that analysis using this model underestimates the settlement and overestimates the ultimate load when compared to that of the experimental study, while there are excellent results of theoretical analysis around to 95 % in case of consolidation settlement. It can be concluded that the soft soil model gives good results for the simulation of immediate and consolidation settlement, this finding is in agreement with Wani [10], however, the soft soil model is suitable for analysis the behavior of soft and compressible clayey soils.

Table 2: Input parameters of soil used in the validation model.

Description	**Symbol**	**Unit**	**Value**
F.E. Model	SSC	-	Soft soil creep
Type of model	-	-	Drained
Lambda	λ	-	0.047
Kappa	K	-	0.027
Mu	m	-	0.014
Poisson’s ratio	v	-	0.4
Cohesion	c_u	kPa	20
Angle of friction	Ø	°	5

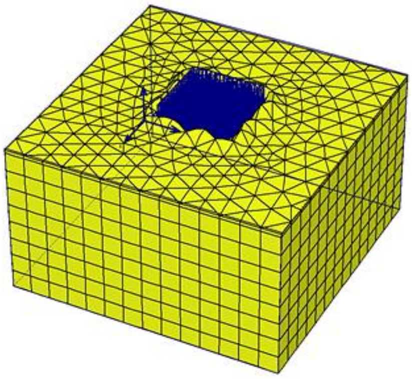

Fig. 4: Geometry of simulated model for validation case.

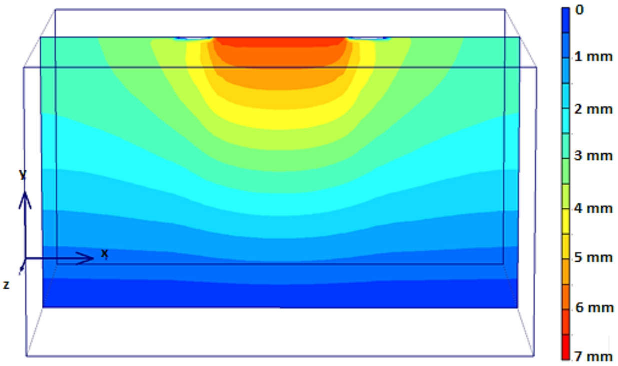

Fig. 5: Contour of vertical displacements under loading of the validation case.

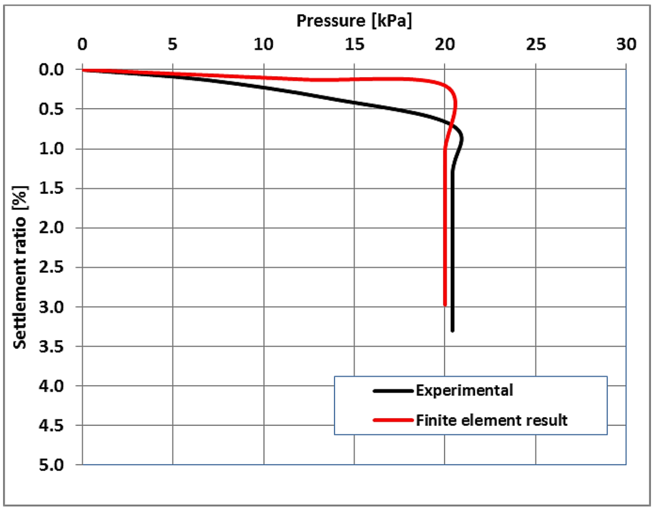

Fig. 6: Comparison between numerical analysis and experimental results.

4 Parameters studies

In order to investigate the settlement of full-scale cases, a square shape foundation with a width B of 10 m was adopted in all cases studies. Table 3 shows the parameters considered in numerical analysis, where the load is applied as a uniform pressure with a state of rigid foundation case.

Table 3: Parameters studied.

No.	Parameter	Values
1	Soil cohesion [kPa]	20, 60, 100 and 140*
2	Pressure [kPa]	20*, 60, 100 and 140
3	Layer thickness [m]	30*, 20 and 10

* This parameter is kept constant when studying the other.

5 Results and discussions

The result of the variation of three parameters studied on the behavior of the foundation for immediate and consolidation settlement is explained below. It is essential to mention that the input parameters used in the validation of a small model produced high values of settlement in the full-scale foundation, as the soil was remolded in a model test, so other input parameters are used in full-scale cases, as can be seen in Table 4. The values of *Lambda*, *Kappa*, and *Mu* are calculated by program default depending on the values of the compression and swelling index chosen for each soil condition.

Table 4: Input parameters used in the soft soil creep model for different soil cohesion.

Soil cohesion [kPa]	20	60	100	140
Compression index (*cc*)	0.1	0.06	0.03	0.02
Swelling index	0.02	0.006	0.003	0.002
Lambda (λ)	0.023	0.015	0.008	0.0057
Kappa (K)	0.009	0.0029	0.0016	0.0011
Mu (m)	0.0045	0.0015	0.0008	0.00057
Poisson's ratio (v)	0.4	0.4	0.4	0.4
Angle of friction (Ø)	5	5	5	5
Initial void ratio (e_0)	0.93	0.74	0.6	0.5

5.1 Variation of soil cohesion

Typical results of the time-settlement curve of raft rested on clay with soil cohesion *cu* equal 20 kPa can be seen in Fig. 7. The effect of variation of soil cohesion is shown in Fig. 8a–d, it seems that an increment of soil cohesion from 20 to 140 kPa decrease significantly the settlement ratio from 25 % to about 0.5 %, this means that for a weak soil, which has the value of cohesion more than 60 kPa, the shallow foundation on deep clay is not appropriate since the settlement will be great and which is practically not acceptable.

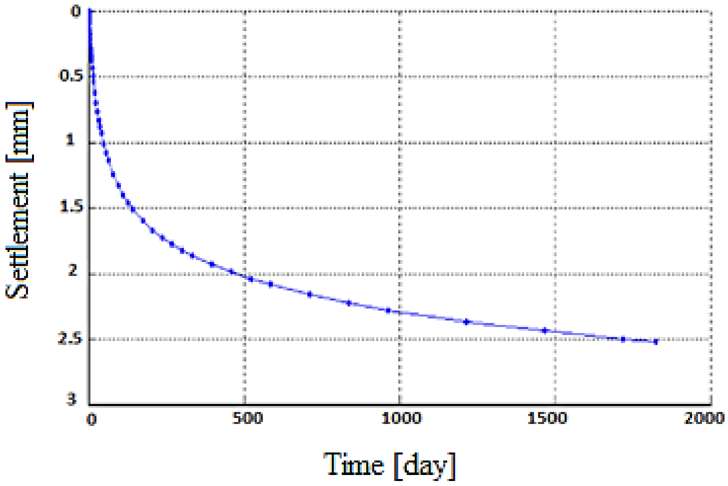

Fig. 7: Time- settlement curve of raft foundation: B = 10 m, c_u = 20 kPa.

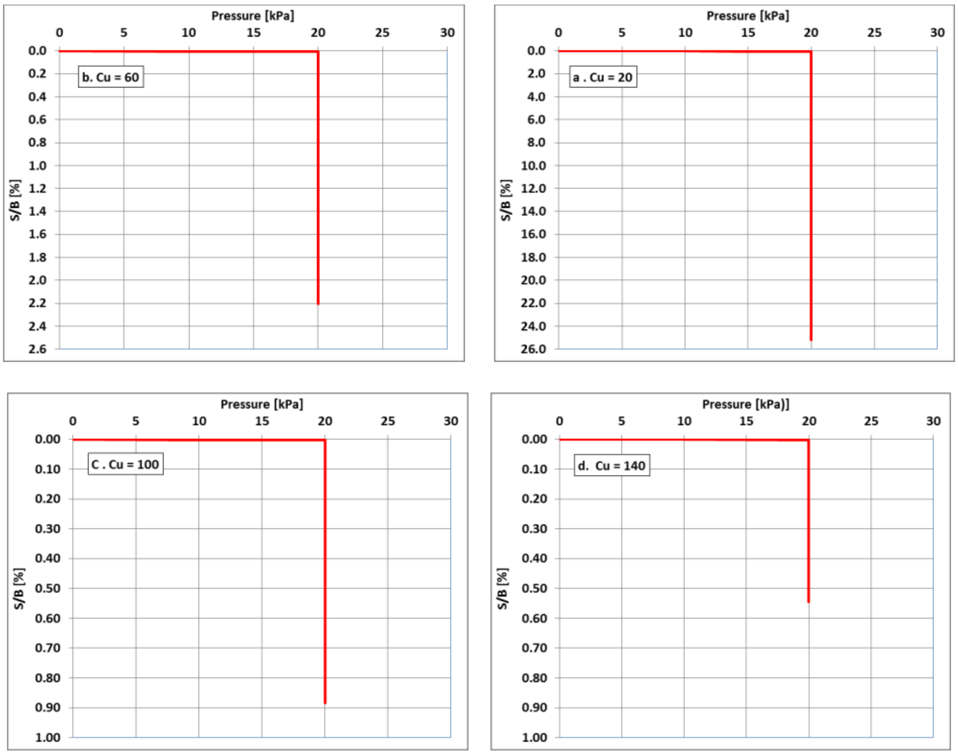

Fig. 8: Effect of variation soil cohesion on the pressure-settlement ratio relationship: a) c_u = 20 kPa, b) c_u = 60 kPa, c) c_u = 100 kPa, d) c_u = 140 kPa.

5.2 Variation of loading pressure

The pressure applied on the foundation q with changing from 20 kPa to 140 kPa, where undrained cohesion of soil was 140 kPa, as shown in Fig. 9a - d, the settlement ratio changed from 0.5 % to 1 %, the findings indicated that in all cases the total settlement was within an acceptable range of the recommendation of Skempton and McDonald [11], they suggested the maximum permissible settlements of raft foundation in clay is between 76 to 127 mm. It can be concluded that for very stiff clay of depth equal to three times the raft width; the applied load can reach a value as long as the cohesion of clay and the total settlement remains within the permissible limits unsimilarly to the weak clay condition.

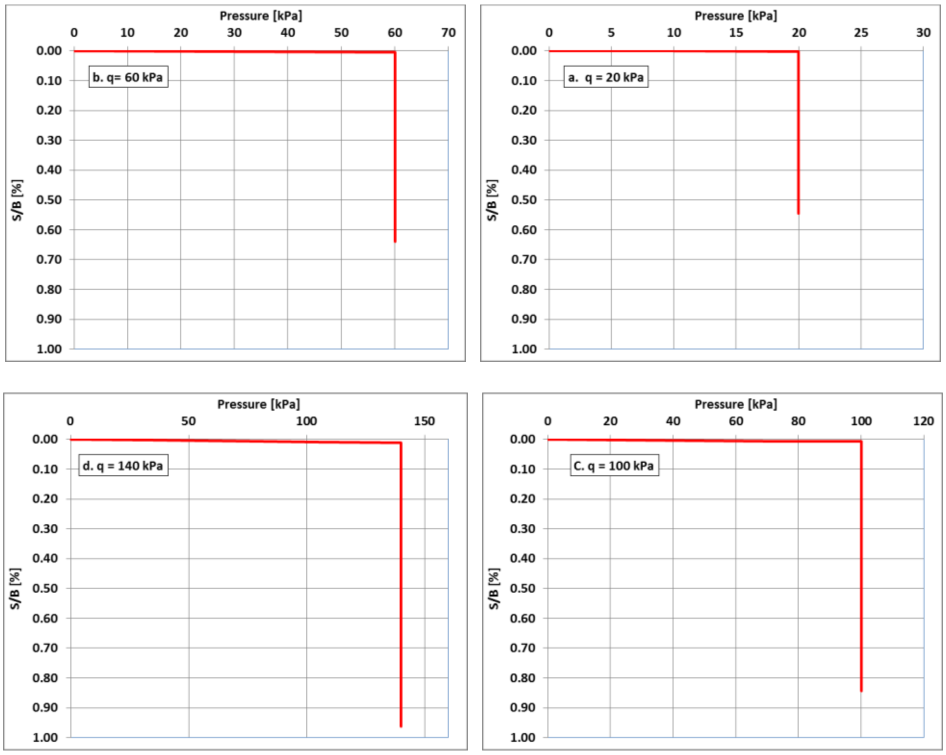

Fig. 9: Effect of variation applied pressure on the pressure-settlement ratio relationship: a) q = 20 kPa, b) q = 60 kPa, c) q = 100 kPa, d) q = 140 kPa.

5.3 Variation of layer thickness

For the purpose of investigating the effect of the layer thickness of soil, it was changed from 30 m to 10 m; where soil cohesion was 140 kPa, the results can be seen in Fig. 10a – c, and it shows that the settlement ratio decreases from 25 % to about 15 %, this indicates that doubling the clay layer from one time to three times of raft width increases the total settlement by about 66 %.

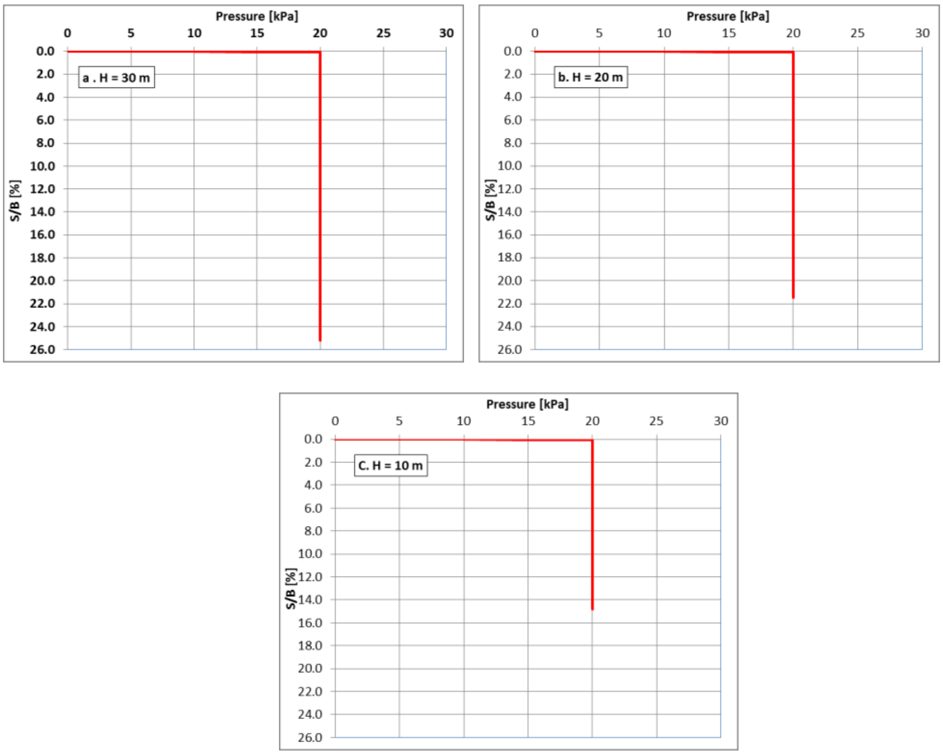

Fig. 10: Effect of layer thickness on the pressure-settlement ratio relationship: a) H = 30 m, b) H = 20 m, c) H = 10 m.

5.4 Results summary

The results of the studied cases of immediate and consolidation settlement are described in Table 5, it can be noted that, in general, the consolidation settlement is much higher than the immediate in clayey soils, this can be attributed to the fact that the weak clay soils contain a high percentage of water, which increases the time and value of consolidation settlement consequently, however, the average of immediate to consolidation settlement was equal to 0.3 % in the case of 20 kPa pressure, then the ratio increases with rising applied pressure until it reaches 1.2 %. This means that the consolidation settlement controls the value of the total settlement, especially in the thicker clay layers.

Table 5: Summary of settlement results for cases studied.

Case No.	c_u [kPa]	q [kPa]	Layer thick. [m]	Immediate settl. [mm]	Consolidat. settl. [mm]	Ratio of immed. to consolid. [%]
1	20	20	30	6.1	2521	0.24
2	60	20	30	0.9	220	0.38
3	100	20	30	0.3	89	0.35
4	140	20	30	0.2	54	0.31
5	140	60	30	0.5	64	0.78
6	140	100	30	0.8	84	0.97
7	140	140	30	1.1	96	1.18
8	20	20	20	5.6	2149	0.26
9	20	20	10	4.5	1480	0.30

5.5 Comparison of predicted and calculated settlement

In addition to the numerical method using the Plaxis program, in this paper, it was used theoretical equations to calculate the settlement of the raft foundation to conduct a comparison between the calculated with the predicted settlements. The foundation is analyzed as a rigid footing; thus the settlement was considered uniform in the calculation.

5.5.1 Immediate settlement

Immediate settlement of a rigid raft foundation can be calculated by the equation reported by Ishibashi and Hazarika [9], as mentioned below, equation (1)

$$S_i = \frac{q\,B}{E}\,(1 - \mu^2) I_p, \tag{1}$$

where S_i is the immediate settlement, μ is Poisson's ratio of soil, E is Soil modulus of elasticity, q is the pressure at the foundation base, B is foundation width, I_p is Influence factor.

It was used an influencing factor equal to (0.99) for rigid square footing [12] and $\mu = 0.4$, so Table 6 represents the ranges values of modulus of elasticity of clayey soil of different consistencies in the undrained state, Bowels [13]. In the absence of more accurate data, the values in this table can be used.

Table 6: Typical values of modulus of elasticity for clay, Bowels [13].

Clay consistency	Modulus of elasticity [kPa]
Very soft	2 000 – 15 000
Soft	5 000 – 25 000
Medium	15 000 – 50 000
Hard	50 000 – 100 000

5.5.2 Consolidation settlement

The calculation of consolidation settlement of foundation by using the expression presented by Das & Sobhan [14], equation (2), as suggested by many researchers, Hemeda [15], where the analysis of vertical stress $\Delta \bar{P_0}$ according to a stress distribution of 2:1 method. For a more accurate result, the clay layer is divided into sub-layers of 1 m thick, then is find the summing settlement of all layers. According to the results of calculated and predicted settlement using the program shown in Table 7, it was found that the numerical analysis showed a lower value of the calculated immediate settlement compared to the predicted results, so the theoretical equation did not take into account the thickness of clay layer, as in case 1, 8 and 9. Regarding the consolidation settlement, the results were close except for the soft clay condition, c_u = 20 kPa, this may be due to the low value of the compression index that was adopted in the program that produced low values.

$$S_i=\frac{C_c}{1+e_0}\,H\,\log\frac{\bar{P_0}+\Delta\bar{P_0}}{\bar{P_0}}, \tag{2}$$

where c_c is compression index, e_0 is initial void ratio, H is the thickness of the compressed layer, $\Delta \bar{P_0}$ is the change in effective stress between initial and final condition. $\bar{P_0}$ is initial effective overburden. Moreover, it was used the value of the initial void ratio and compression index from Table 4.

Table 7: Comparison of predicted and calculated settlement.

Case No.	c_u [kPa]	q [kPa]	Layer thickness [m]	Calculated immediate settlement [mm]	Calculated consolidation settlement [mm]	Ratio of predicted to calculated immediate sett.	Ratio of predicted to calculated consolidation settl.
1	20	20	30	8.3	109.7	0.73	23.0
2	60	20	30	2.8	68.9	0.31	3.2
3	100	20	30	1.7	36.3	0.19	2.4
4	140	20	30	1.2	24.0	0.14	2.3
5	140	60	30	3.6	49.1	0.14	1.3
6	140	100	30	5.9	66.5	0.14	1.3
7	140	140	30	8.3	80.5	0.14	1.2
8	20	20	20	8.3	107.7	0.68	20.0
9	20	20	10	8.3	100.9	0.54	14.7

5.5.3 Limitation

The limitation of this study, the study did not take into account the secondary settlement because it takes long periods of time to the end of the consolidation settlement and it also occurred in a special type of soil. Also, a further similar study can be conducted to other foundations types such as deep foundations.

6 Conclusion

From the results of this study, it can be concluded that:

1) The time of completing most of the consolidation settlement is not exceeded about one week and it was less than the theoretical expected time for a small-scale model footing in clay as the dissipation of the excess pore water pressure in three directions.

2) In clayey soil, the simulation of the soft soil model underestimates the immediate settlement by about 30 %, while gives excellent results for predicting the consolidation settlement of rafts.

3) The shallow foundation on deep weak clay of cohesion was lower than 60 kPa, is inappropriate, since the settlement will be great and practically not acceptable.

4) In the case of a shallow foundation resting on very stiff clay of depth equal to three times the raft width, the applied load can reach a value as long as the cohesion of clay and the total settlement remains within the permissible limits.

5) The total settlement of shallow raft foundation rested on a clay layer of depth was three times raft width was increased by about 66 % than a layer of one-time raft width.

6) The consolidation settlement is much higher than the immediate in clayey soils, however, the average of immediate to consolidation settlement is equal to 0.3 % for pressure 20 kPa, and increases with rising of the applied pressure until reaches 1.2 %.

7) The numerical analysis showed a lower value than calculated for immediate settlement, while for consolidation settlement, the results were almost similar except for the soft clay condition, c_u = 20 kPa.

8) Finally, in order to obtaining more accurate results in the consolidation settlement calculation of a thick layer, the clay layer must be divided into sub-layers of about 1 - 2 m, then find the summing settlement of all layers.

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