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Comparison between Theoretical and Experimental Behavior of Shallow Foundation in Cohesive Soil

Baraa A. Al-Dawoodi *, Mohaned Q. Waheed, Falah H. Rahil

Civil Engineering Dept., University of Technology -Iraq, Alsina'a street, 10066 Baghdad, Iraq.
*Corresponding author Email: bce.19.32@grad.uotechnology.edu.iq

HIGHLIGHTS

- Clay with (cu) of 25 and 70 kPa, simulation by the HSs model gave the best results.
- Footing capacity by MC model in stiff clay increased with increasing friction angle.
- Increase soil modulus from (10 to 30 MPa) cause increase in bearing capacity 23 %.
- MC matches curve at elastic zone then over predicts at the final stage of loading.

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ABSTRACT

This paper discusses a finite element analysis of shallow footing subjected to axial loading rested on different types of cohesive soil by using a computer program called PLAXIS-3D (V.20) software. The behavior of cohesive soil is simulated using several constitutive models (Mohr-Coulomb model, Hardening soil model, and Hardening soil with small strain stiffness model in order to find the best match between theoretical and experimental results).Two cases are considered square and rectangle. Moreover, some parameters that affect the load settlement relation curve; such as internal friction angle and soil modulus elasticity were investigated. It was found that the simulation by the Hardening soil model with small strain stiffness gives better results in both cases of the square and rectangle (C=25) and square footing (C=70). It was also observed that increasing the foundation width led to increases in bearing capacity, however, there was an increase of bearing capacity to about (9.45 %) for an increase in footing width of (6.25), so it was about (17%) for (12.5). For square footing in stiff clayey soil, the bearing capacity of the soil increases to about (23%) when the range of the modules of elasticity of soil increases from (10000 to 30000KN/m^2).

1. Introduction

Shallow foundations are extensively used for the purpose of supporting structures of all sizes and derive their bearing capacity from the soil that supports them. Therefore, they are regularly inserted up to some meters into the soil strata to get a suitable soil. Two limit states are required for designing the shallow foundations:

- The foundation should be safe from the shear failure of the soil beneath it (bearing capacity failure).
- It Should not undergo excessive settlement.

Because the nature of the soil is complex, the development of constitutive models is able to know the 'true' behavior of the soil. It is considered the important aspect of analyzing geotechnical structures, like guess of shallow foundation settlements. The constitutive models, in general, that perform in trade software are so easy (Mohr-Coulomb model (MC), Hardening soil model (HS), Hardening soil model with small-strain stiffness (HSsmall)). Despite the complexity of the component of the soil and the new constitutive relationship that was recently developed (Carve (1990), Champion (2000), Dayflies and Manzari (2004), Muir Wood (2004), as recently suggested by Muir Wood (2004)) so as to permit geotechnical engineers to solve experimental issues considering more reasonable soil behavior, more effort should be made to implement new constitutive soil models in numerical trade codes [5-8]. Moreover, the research goal is to explore the best matching of the finite element model with the experimental load-displacement curve using different finite element models and to study the effect of some parameters on the load settlement relation curve like the size of footing, modulus of elasticity, and internal friction angle.

2. Background

In this paragraph, we briefed the previous studies that have been studied by several researchers, and among what was produced:

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Fattah et al. [9] conducted laboratory testing on undisturbed clay soil samples that were performed in order to characterize the stress-strain behavior of the residual soils in Sao Paulo sedimentary deposit. Seven models are used; namely: linear elastic, Duncan-Chang hyperbolic, Mohr-Coulomb, Cam clay, modified Cam clay, new Mohr-Coulomb and Cap model. The finite element program SAGE-CRISP was used in this work. They concluded that the results of the Cam clay and Duncan Chang models are the closest to the experimental data under low confining pressures. Ornek et al. [10] performed numerical analyses utilizing PLAXIS 2D finite-element program for circular footing. Before carrying out the examination, the verification of the constitutive model was verified utilizing field tests conducted by researchers with seven various footing diameters of up to (0.9 m) and with three several partial replacement thicknesses. They concluded that the settlement anticipated by the numerical analysis is generally in excellent agreement with the test results. Ibrahim et al. [11] conducted a numerical analysis using the finite element software PLAXIS 2D for the footing resting on soft clay. They concluded that the soft soil model foresees more precise settlements than the Mohr-Coulomb calculation. Naeini and Theravada [12] conducted a plate load test (PLT) for clay soil with a percentage of sand or without sand, where a plate with 30 to 45 cm diameter was loaded gradually and the soil settlement was observed stage by stage. Plate load test was simulated by (ABAQUS. V. 6.9) by using Mohr-Coulomb model. They compared the results obtained from the plate load test with the numerical modeling results. The outcomes show that the settlements obtained from the numerical simulation are rise to contrast with PLT, and the reason is due to the change of circumstances of the soil at the site, for example, stress and soil behavior. It has been seen that utilization of 2.5 to 3.25 of initial elasticity modulus E0 , such an input parameter of programming can lessen the mistake rate, up to 15% for cohesion soils. Waheed and Asmael [13] carried out a numerical analysis using the Plaxis-3D program on the behavior of shallow foundation rested on clayey soil and subjected to vertical axial loading. They found that increasing the foundation width does not have a significant effect on the value of the bearing pressure, so that the scale effect could not be observed. Waheed and Asmael [14] studied simulation of shallow foundation using different models of finite elements using Plaxis-3D program and compared the numerical result with the experimental one. Three models were utilized during modeling the soil behavior, including Mohr-Coulomb, Hardening, and soft soil model. The behavior of small and large-scale shallow foundations under axial loading in clayey soil was studied. It was found that for the small-scale foundation, the simulation of the Mohr-Coulomb model requires great care to use this model. The soft soil (creep) model is invalid (compared with the experimental curve). The representation using the hardening soil model is more realistic and gives better results. In the case of the large-scale foundation, these three models can be used for simulation, where the simulation of the hardening soil model is the best.

3. Methodology

By utilizing the program of finite element PLAXIS-3D (V.20) software, various models for different cohesive soil and footing are analyzed numerically. The geometry, mesh, and properties of models are described bellow:

3.1 Geometry of the model

Figures 1 and 2 show the geometry of the two footings resting on the cohesive soil. The dimensions of the geometric model were chosen according to the criteria, with the ratio being as suggested by PLAXIS-3D (V.20) software tutorial Manual [15]. The mesh consists of three-dimensional 10-Node tetrahedral elements that were used to model and represent the soil and 6-Node plate was used to simulate the behavior of footing, as shown in Figure (3). The number of elements to be chosen for the idolization is related to the accuracy desired, the size of the element, and the number of degrees of freedom involved. Although an increase in the number of elements generally means a more accurate result, for any given problem, there will be a certain number of elements beyond which the accuracy cannot be improved by any significant amount [17]. Several trials were made to get the suitable number of elements in the finite element mesh, where in this study, we used generated mesh (medium) both in soil and footing, then double refine mesh for footing. The number of elements depends on the geometry of the cases analyzed [18, 19].

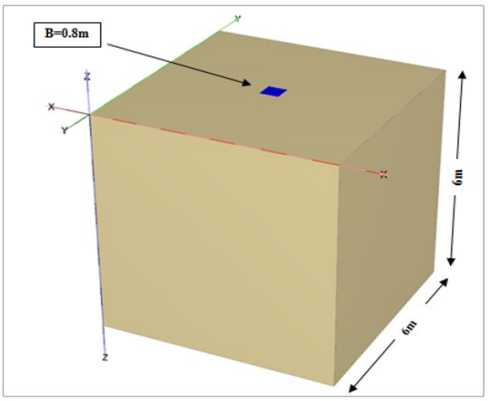

Figure 1: The geometry of model-footing-1 (C=70)

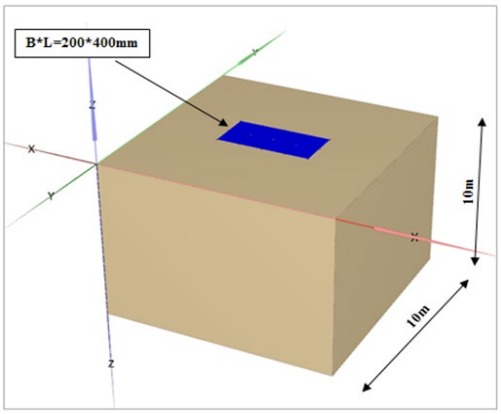

Figure 2: The geometry of model-footing-2 (C=25)

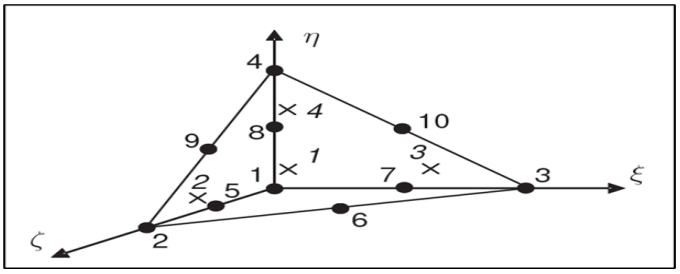

Figure 3: 3D soil element (10-node tetrahedrons) [16]

3.2 Material properties

The footing is assumed to behave elastically while the hyperbolic model is used to describe cohesive soil behavior. The material properties used for the analysis are shown in Table1. Two types of cohesive soil were employed in this study, properties of soil with (C=70) were adopted from the work of WA heed and Montez [14], where in this case the footing shape is square with (0.8m) width and the parameters of the author in the case of drained [14]. While the properties of soil with (C=25) were adopted from the work of Rahil, F.H. (2007) and the footing represents a rectangle with a dimension of (200mm*400mm) and the parameters are for authoring case of untrained [20]. The properties of clay employed in this paper can classify the cohesive soil according to shear strength parameters to two types: the first, at C=25 soil classified to medium, so that when C=70, the soil is stiff. C70 and (c25, c16).

Table 1: The input properties of the studied soil [14][20]

Material	**Soil 1 (C=70)**			**Footing**	**Soil 2 (C=25)**			**Footing**
Model name	MCM	HSM	HSs M	Linear Elastic	MCM	HSM	HSs M	Linear Elastic
Type of drainage	Drained	Drained	Drained	Non- porous	Untrained B	Untrained B	Untrained B	Non- porous
(γ) (KN/m^3)	17	17	17	78.5	20	20	20	27
(γ dry) (KN/m^3)	15	15	15	-	17	17	17	-
c` (kPa)	70	70	70	-	25	25	25	-
ø°	10	10	10	-	0 °	0 °	0 °	-
$E`$ (kPa)	10000	-	-	200×10^6	900	-	-	70×10^6
$\nu`$	0.4	0.4	0.4	0.26	0.4	0.4	0.4	0.4950
E_{50}^{ref*}	-	10×10^3	10×10^3	-	-	500	300	-
E_{oed}^{ref}	-	17×10^3	22×10^3	-	-	500	300	-
E_{ur}^{ref}	-	30×10^3	30×10^3	-	-	1500	900	-
Exponential Power m *	-	1	1	-	-	1	1	-
Initial shear modulus G0*	-	-	135×10^3	-	-	-	7500	-
Shear strain ϒ0.7*	-	-	6000×10^{-3}	-	-	-	4×10^{-6}	-

*Estimated based on correlations of Praxis 3D -2020 user manual [21]

4. Constitutive models used

Several models have been used, which will be presented briefly:

4.1 Mohr-Coulomb model (MC)

The Mohr-Coulomb model explains soil behavior of elastic-perfectly plastic including five input parameters, E and ν for soil elasticity, φ and c for soil plasticity, and ψ as an angle of militancy, and it was considered most commonly utilized than others. According to Brink grave [21], to get a first assessment of deformations, it was recommended to use the Mohr-Coulomb because this model does not require further soil data.

4.2 Hardening soil model (HS)

The Hardening Soil model is the same as the Mohr-Coulomb model, however, it is further developed and dissimilar from the Mohr-Coulomb model in that stiffness's in the Hardening Soil model increases with pressure. The Hardening-Soil model is appropriate for all soils; however, it does not represent the viscous effects such as creep and stress relaxation. Three different

stiffness parameters employed in the Hardening soil model are ($E_{50,}$), the triaxial loading stiffness, E_{ar}, then triaxial unloading stiffness, and $E_{oed,}$ the odometer loading stiffness for several kinds of soil [21].

4.3 Hardening soil model with small-strain stiffness (HS small)

The Hardening Soil model with small-strain stiffness performed in PLAXIS-3D (V.20) software is based on the Hardening Soil model and it employs nearly similar parameters. In fact, two extra parameters are required to illustrate the variety of stiffness with strain:

G_0 the initial or very small-strain shear modulus

$\gamma_{0.7}$ the shear strain level at which the secant shear modulus Gs' is reduced to about 70% of G_0 [21].

5. Results and Discussion

In this segment, we will outline the result obtained from the analysis of the parameters that influence the behavior of the foundation.

5.1 Effect of the constitutive model utilized

To study the simulation utilizing various models, the analysis of the pressure–settlement curve is done utilizing the inputs previously referenced in Table (1). The deformed mesh of footing models by Praxis and the distribution of vertical displacement of the case study are shown in Figures (4, 5 and 6). The comparison among numerical and experimental load-settlement curves is shown in Figures (6 and 7). It can be seen that the consequence of the Mohr-Coulomb model appears to be matching in the elastic zone, then, it is overestimated and deluded at the last level of loading because it behaves as linear elastic perfectly-plastic. It was seen that the simulation by the Hardening soil model with small-strain stiffness gives better results contrasted with Mohr-Coulomb because the Hardening models elastoplastic and its simulation is closer to the soil behavior. It was also noted that the results are in agreement with the results of Waheed and Asmeal [13][14].

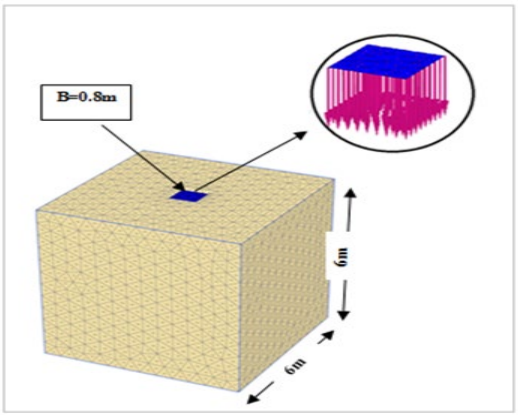

Figure 4: The geometry model and the deformed mesh of footing1 (c=70)

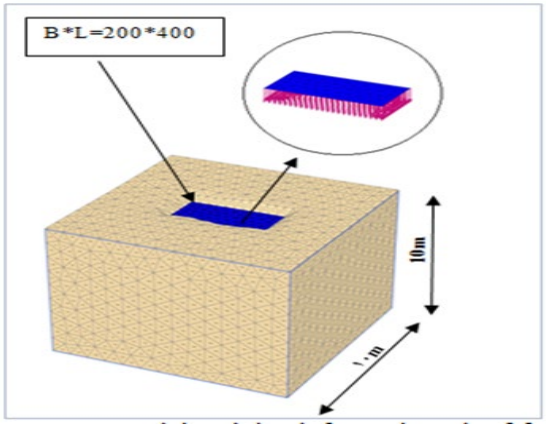

Figure 5: The geometry model and the deformed mesh of footing2 (c=25)

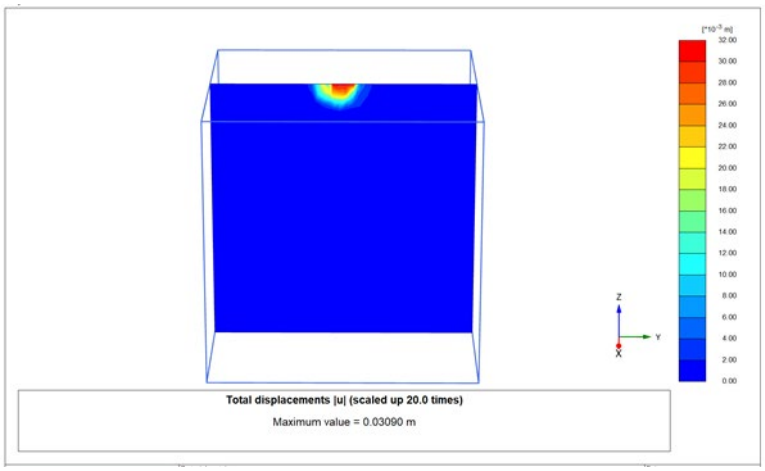

Figure 6: Distribution of vertical settlement under loading of foundation at the center of the models. - Footing for Mohr Coulomb Model

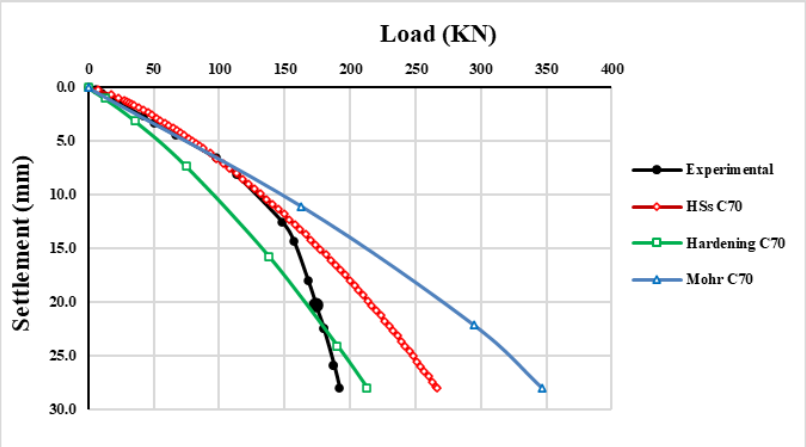

Figure 7: Load – settlement response of various soil models for footing 1(C=70)

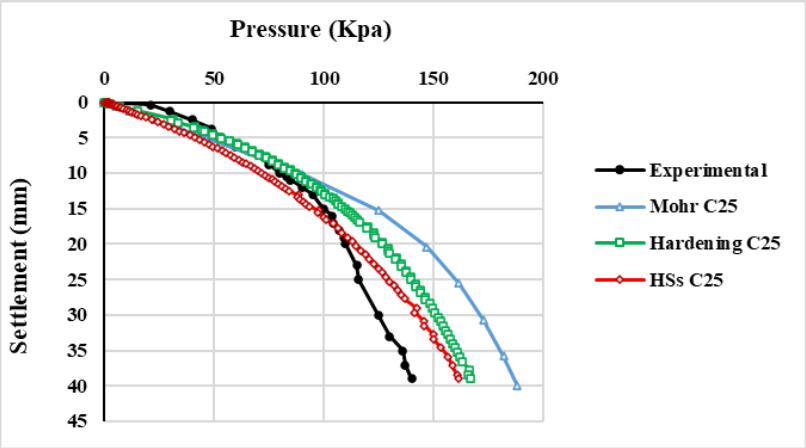

Figure 8: Load – settlement response of various soil models for footing 2(C=25)

5.2 Effect of footing size

Three cases were considered in size of a square shape, 80 cm, 5 m, and a width of 10 m. The results of the representation of pressure versus normalization settlement over the foundation width (S/B) for the three models are shown in Figures (9,10 and 11). It may be seen that there was an increment in the bearing capacity at (10%) footing width, with increasing the width of the foundation, with various rates, as appeared in Table 2. It tends to be seen that at a proportion of increasing in the raft width of (6.25), there was an increment in bearing capacity to around (9.5 %) so that in the state of incremental foundation width of (12.5), the average equals (17.4 %). The reason for this is due to the presence of the angle of friction in the inputs used to represent this case, which leads to a slight increase in the bearing capacity by increasing the width of the foundation.

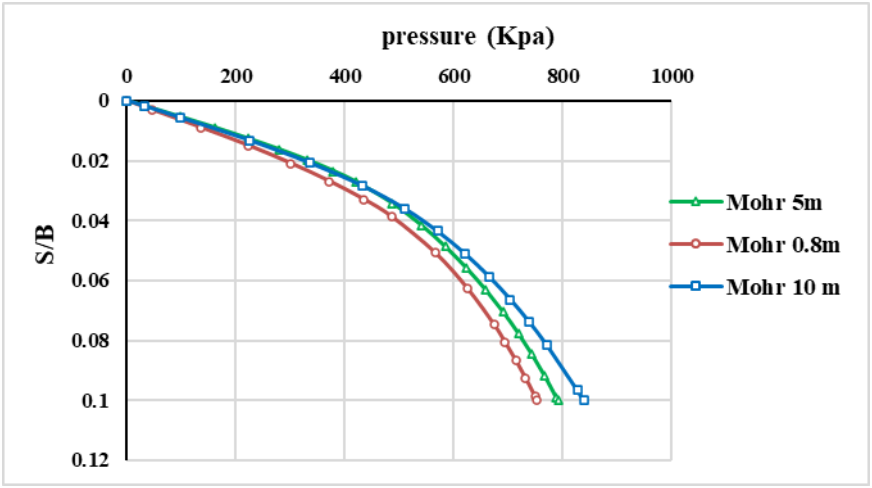

Figure 9: The impact of the size of foundation on the relationship between pressure and settlement over the width ratio (S/B) (Mohr-Coulomb models) for footing 1

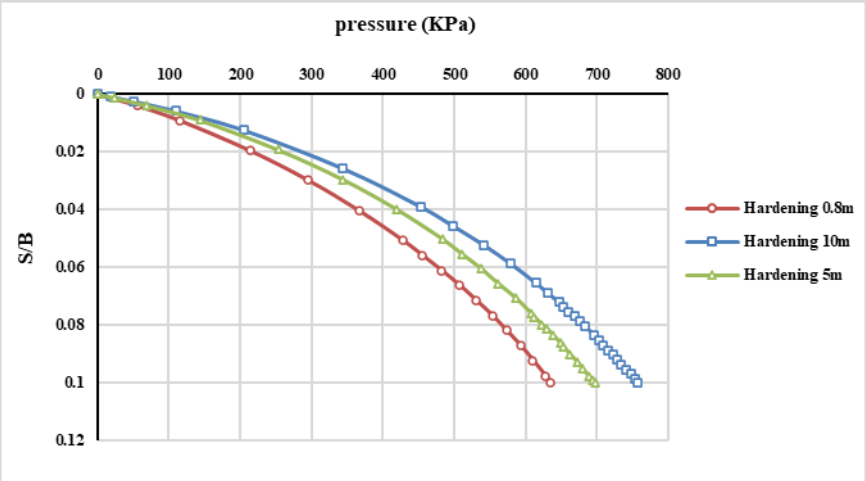

Figure 10: The effect of the size of foundation on the relationship between pressure and settlement over the width ratio (S/B) (Hardening soil models) for footing 1

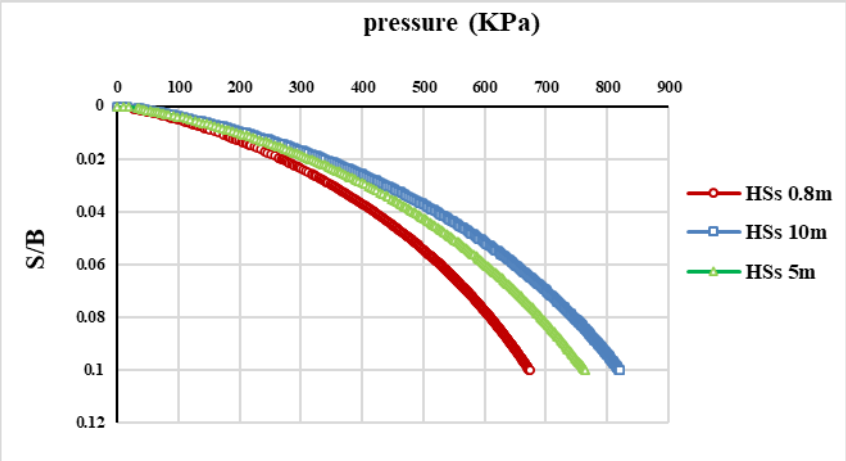

Figure 11: The impact of the size of foundation on the relationship between pressure and settlement over the width ratio (S/B) (Hardening soil models with small strain stiffness models) for footing 1

Table 2: Percentage of increasing in the bearing capacity with the raft width for soil 1

Models' Types	**Results of raft width (5m)**		**Results of raft width (10 m)**	
	Increase of bearing capacity with respect to raft width (0.8) (%)	***Ratio of footing width with respect to raft (0.8m)***	***Increase of bearing capacity with respect to raft width (8 cm) (%)***	***Ratio of footing width with respect to raft (0.8m)***
MC	5.06	6.25	11.30	12.5
HS	9.89	6.25	19.139	12.5
HSS	13.41	6.25	21.88	12.5
Average	9.45	6.25	17.44	12.5

5.3 Effect of internal friction angle

Figure 12, illustrates the effect of the internal friction angle on the bearing capacity for simulating the case study of footing- 1(C=70) and for Mohr-Coulomb model. Then, it was observed that when the internal friction angle increased the bearing capacity increased, as the increase in the angle of internal friction leads to an increase in the shear strength of the clay and thus an increase in the bearing capacity.

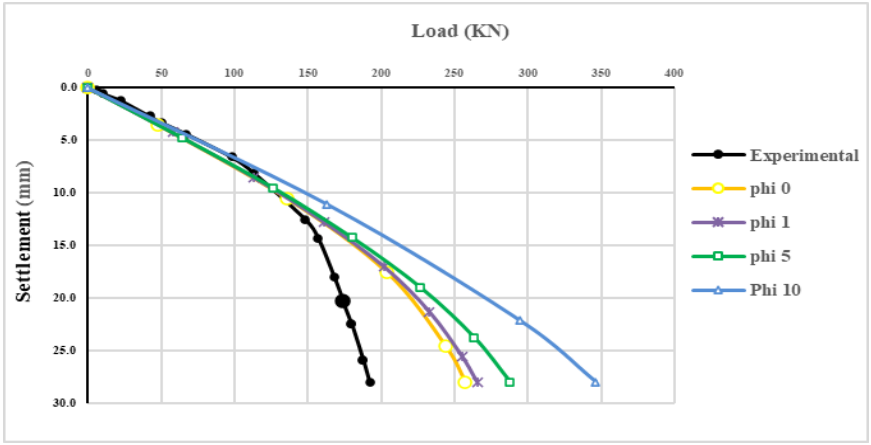

Figure 12: The effect of the internal friction angle on load-settlement relationship for Mohr-Coulomb model for footing- 1

5.4 Effect of Soil Modulus of Elasticity

It was observed that changes in the modulus of elasticity of the soil affect the load settlement curve, as shown in Figure 13. The bearing capacity of the soil increases significantly up to 23% with an increase in the elasticity modulus of the soil from (10000 to 30000KN/m^2). The reason for this is attributed to the fact that soil modulus is a measure of the stiffness of a material or the resistance to elastic deformation under load, the higher the value of soil modulus, the greater the resistance of the soil to stress and deformation, so the value of the bearing capacity of the soil will increase.

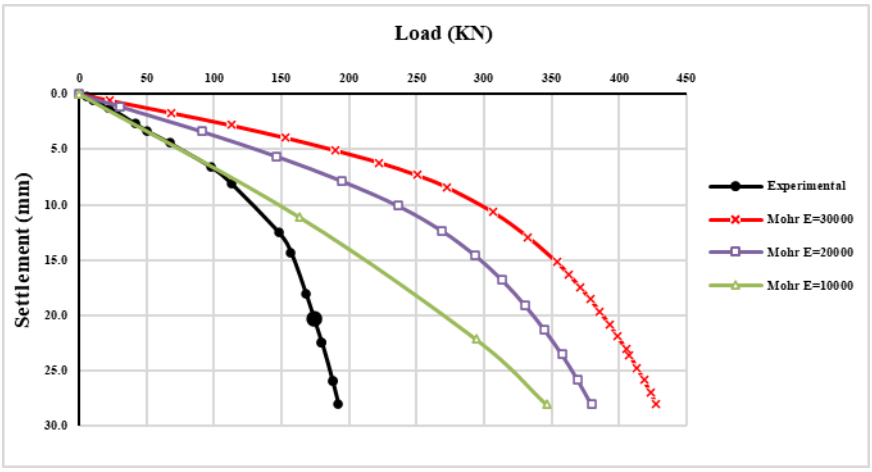

Figure 13: The effect of modulus of elasticity of soil on load-settlement relationship using Mohr-Coulomb model for footing- 1

6. Conclusion

Depending on the results of the current study that was conducted by a numerical investigation to analyze the load–settlement relation of footing exposed to vertical load rested on different clayey soils using PLAXIS-3D (V.20) software, the following points can be concluded:

1) For a small scale foundation, the simulation of the Mohr-Coulomb model matches the curve at the elastic zone and then over predicts at the end level of the loading curve, so great care must be taken to use this model in both cases, rectangle (C=25) and square footing (C=70).
2) The simulation by the Hardening soil model with small-strain stiffness provides the best results in both cases of the rectangle (C=25) and the square footing (C=70).
3) When the footing width increases the bearing capacity increases. It can be seen that at a ratio of increase in the raft width of (6.25) there was an increase in bearing capacity to about (9.45 %) so that in the case of increasing the raft width of (12.5) the average equals (17.44%).
4) The increasing of the internal friction angle led to an increase in the bearing capacity of stiff clayey soil C=70 for Mohr-Coulomb model.
5) For stiff clayey soil (C=70)**,** the bearing capacity of the soil increases to about (23%) when the range of the modules of elasticity of soil increases from (10000to 30000KN/m^2).

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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