Finite Element Analysis of the Load-Settlement Behavior of Large-Scale Shallow Foundations on Fine-Grained Soil Utilizing Plaxis 3D

Asmaa G. Salih[1](✉), Ahmad S. A. Rashid[1], and Nihad B. Salih[2]

[1] School of Civil Engineering, University Teknologi Malaysia, Johor Bahru, Johor, Malaysia
asmaagheyathsalih@gmail.com, ahmadsafuan@utm.my
[2] Department of Water Resources Engineering, University of Sulaimani, Sulaimaniyah, Iraq
nihad.salih@univsul.edu.iq

Abstract. Numerical modelling with the implementation of the finite element method can be used to provide valuable data with a high level of accuracy, success, and time-saving. Selection of the convenient soil model and appropriate soil parameters are required in numerical modelling to achieve realistic and accurate results. In this study, three-dimensional finite-element models were developed to simulate the case of a raft foundation system of a structure resting on a soil profile located across Sulaymaniyah Governorate, Northern Iraq. The square mat foundation was utilized in various systems of various areas (10 × 10 m^2; 15 × 15 m^2; 20 × 20 m^2) with different thicknesses of 0.4, 0.6, and 1.0 m in the embedment depth modelled using Plaxis 3D software. The models were simulated to investigate the effect of key parameters dominating the performance of the foundation system during loading and, accordingly, the settlement occurred due to the applied load, whereas the models were utilized to create an obvious conception about the behavior of the huge size of footing within the soil medium. As a result of the analysis, it is observed that as the dimension of the footing size increases by a ratio of 50% and 100%; the ground settlement decrease with a percentage of 55.7% to 71.2% respectively. Furthermore, findings yielded no considerable effect related to the variation of footing thickness. The results of this study could be considered guidelines to achieve economic design and suggestions for mat foundation system.

Keywords: Shallow foundation · Soil settlement · Numerical modelling · Plaxis 3D

1 Introduction

The primary requirement in shallow foundations design aspect is that the structure's foundation must be safe against possible instability. The soil deposit must have sufficient bearing capacity to support the structural loads transmitted through the foundation. Therefore, the analysis of soil bearing capacity is normally done as a first process to ensure the appropriate safety factor. Consequently, settlement analyses must be carried out as a second procedure [1, 2]. Most shallow foundations systems comprise appropriate bearing capacity; on the other hand, the behavior of most shallow foundations is

M. Karkush et al. (Eds.): ICGECI 2022, *Current Trends in Geotechnical Engineering and Construction*, pp. 249–260, 2023.
https://doi.org/10.1007/978-981-19-7358-1_22

essentially controlled by their settlements. Settlement of soils is known as a critical problem in different engineering applications [3], which engineers and designers strongly consider for risk management in constructing geotechnical buildings. Furthermore, the appropriate settlement prediction plays an important role in preventing structural failure to newly constructed buildings or even existing buildings [4].

Several empirical and analytical design methods have been proposed to estimate the settlement of loaded shallow foundations based on diverse theories. In recent years, the use of finite element method software in the modelling of soil-foundation interaction helped to elucidate certain key variables that can influence the deformation behavior of shallow foundations. This design method provides successful tools for estimating the bearing capacity of foundations under vertical loading and the corresponding settlement.

The aim of this research is to provide a basic platform for a better understanding of the shallow foundation design associated with heavy buildings resting on an expansive soil profile that located in Sulaymaniyah city. Different foundation thicknesses along different loading areas that comprise the structure-foundation systems have been designed and simulated using the finite element method by employing Plaxis 3D software. This analysis method is utilized in order to investigate the effect of the foundation's size on the load-settlement relationship through the comprised zone. This study emphasizes that soil settlement evaluations are necessary to preserve the safety and life of the constructed structures.

2 Study Area

It is well established that soils in Iraq vary from north to south [5] since they show diverse degrees of development according to the effects of the local condition such as calcareous parent materials, geomorphology, semi-dry climatic, and grass [6, 7]. Basically, soils in the Kurdistan region of Iraq are mostly calcareous and originated from limestone and dolomite of different formations [8, 9]. Sulaymaniyah city is located northeast of Iraq near a border with Iran of geographic coordinate Latitude and Longitude 35°33′40″ N and 45°26′14″ E. Generally, Sulaymaniyah city, in its rapid progress in development along with the last decade [10], is witnessing large land development and activities, especially in infrastructure investment. Accordingly, the soils profile and classification of the different locations across the Sulaymaniyah city have been investigated extensively in recent years. Proper determination of pertinent geotechnical engineering properties for soil profile is essential for producing a safe design but not over-conservative. Hence, numerous researches are established on the soil classification and the geotechnical engineering properties of soil. Nevertheless, it seems that the indicated results are limited and need to be more considered.

Azeez [6] conducted his research on soil samples collected from Garmian, Kalar city, alongside the Serwan River. The results showed that the silt content was the dominant fraction, followed by clay and sand in the studied pedons due to the effect of parent material and, to some extent, the geomorphic and climatic conditions. Research on Ranya District and Arbat Sub-District area located in Sulaimaniya Governorate reported by Bapeer et al. [11] and demonstrated that Ranya area is covered by alluvial sediments which consist of clay, silt, and gravel (sand-silt mixture, with clay), whereas Arbat area is covered by Shranish and Kometan Formations which the soil is mostly silt and sand with some clay, in other words, they concluded that the soil in both areas is a mixture between coarse and fine grain texture and are characterized by low to medium plasticity.

Najmaddin et al. [12] reported a study on soil geotechnical characteristics for settlement investigations. The study was carried out on sixty different representative soil samples taken from a distance of 2.0 m from the natural ground surface around the Sulaimaniah city; laboratory experiments addressed that the soil type of the collected specimens was fine-grained soils. Moreover, another study reported by Rashed et al. [13] was conducted on sixty samples collected from different locations of Sulaimani City namely: Qerga, Qularaesy, wllwbe, Rapareen, Bakrajo, Swrga, Kellekn, Kenekewe, Kelespy, Homerekwer, Xewete and Dabashan; this study showed that all soil samples were classified as fine-grained soils. According to the data provided by Abdalqadir et al. [14] and Salih & Abdalla [15], the investigated ground soil samples were found and classified as expansive clayey soil, which responded successfully to the added stabilization materials.

3 Shallow Foundation Design

The geotechnical design of the structure foundation on clayey soils (compressible materials) is considered one of the most complicated aspects of foundation engineering Chao and Nelson [16].

For situations where heavy structures must be constructed on soft or expansive soils over a limited area; a mat foundation can be selected for the proposed design. Furthermore, it is common to use mat foundations where the foundation soil has a low/poor bearing capacity where settlements may be a problem [17]. Besides that, if spread footing is used and the area of all the spread footings was more than 50 percent of the area of the entire structure, a raft/mat foundation should be taken into consideration [18].

Basically, the foundation type must meet performance requirements. However, flat concrete slab mat configuration is the most common shallow foundation design, which covers the whole space beneath a structure and supports all the existing columns and walls. With regard to the significance of the design concept, the stresses induced by the transmitted loads to the soil medium beneath the footing must be within its bearing capacity. A mat footing design must be firm against shear failure and limit the settlements to a tolerable amount of 50 mm [17]. Without utilization the surrounding soil strength of, foundations hardly resist the subjected loads to them in a complicated interaction resulted from the soil's elasto-plastic properties. Away from the behavior of soils, soil-structure interaction is greatly influenced by the methods of construction, structure size, structural components stiffness, and applied loads.

4 Numerical Analysis with Plaxis 3D

Studies of various numerical methods used to model the behavior of soil-structure interaction have been presented by many researchers. Essentially, the advanced numerical modeling method could attain more reliable predictions than the empirical method, especially when the required input data are provided and sufficient information about the common soil conditions is available [19]. Gupta and Mital [20] conducted a study on soil behavior under the loaded rectangular footing using Plaxis software with 2D and 3D models. A comparison of the results obtained demonstrated that the 3D analysis provides more accurate results as compared to the 2D analysis.

Numerical analysis performed using the Plaxis-3D program was carried out by Waheed and Asmael [21] on the behavior of shallow foundations subjected to vertical axial loading in clayey soil, the results of the analysis were in good agreement with measured experimental results. Salimath and Pender [22] investigated the behavior of shallow foundations under fixed vertical load on clayey soil subjected to moment about a centroidal axis; their study concluded that the advanced simulation with the PLAXIS 3D demonstrates the capability of this program to model and analyze complex soil-structure interaction problems with a high degree of accuracy.

5 Material and Methods

5.1 Location of the Study Area

The soil samples were collected from a location in southern Sulaymaniyah city. The soil properties of the studied areas are shown in Table 1. The consistency tests and unconfined compression test were carried out according to ASTM standards. The soil samples classified as medium to high expansive soil.

Table 1. The geotechnical properties of the utilized natural clayey soil.

Soil type	Liquid Limit (LL) %	Plastic Limit (PL) %	Plasticity Index (PI) (%)	Natural moisture content (%)	Unconfined compression strength (q_u) (kN/m^2)
Cohesive soil	87.0	51.0	36.0	47.64	100.75

5.2 Geometry and Boundary Conditions

Plaxis 3D software is the finite element package intended for the three-dimensional deformation analysis of soil layers beneath the foundation structure. Essentially, the results of the analysis are critically affected by the model type and the corresponding soil input parameters. In point of fact, the selected model proposes a mathematical description of the mechanical behaviour of the analysed materials. For such purpose, one of the most widely used models is the Mohr-Coulomb elastic-plastic model. This mentioned model has more implementations than other models and this comes due to its simplicity and lesser required data for developing the study. The input parameters involved, i.e. E and ν for soil elasticity; C = su, $\varphi = 0°$, and consequently $\psi = 0$ as an angle of dilatancy for soil plasticity. Soil parameters adopted in the Mohr-Coulomb model are presented in Table 2.

Table 2. Soil parameters for Mohr-Coulomb model in Plaxis 3D.

Modeling parameters	Modeling Type	γ_{sat} (kN/m³)	E (kN/m²)	v_u	S_u (kN/m²)	φ (°)
	Undrained	17	2500	0.495	50	0

6 Finding and Discussion

According to the displacement analysis of 10% of the footing width (B = 1 m, the allowable designing displacement = 0.1 m); the isolated square footing of (1 × 1) m^2 responds to a deformation behavior within 25 mm of settlement as shown in Fig. 1, and the corresponding soil bearing capacity matches the allowable soil bearing capacity (q_u) that obtained from the unconfined compression test as presented previously in Table 1.

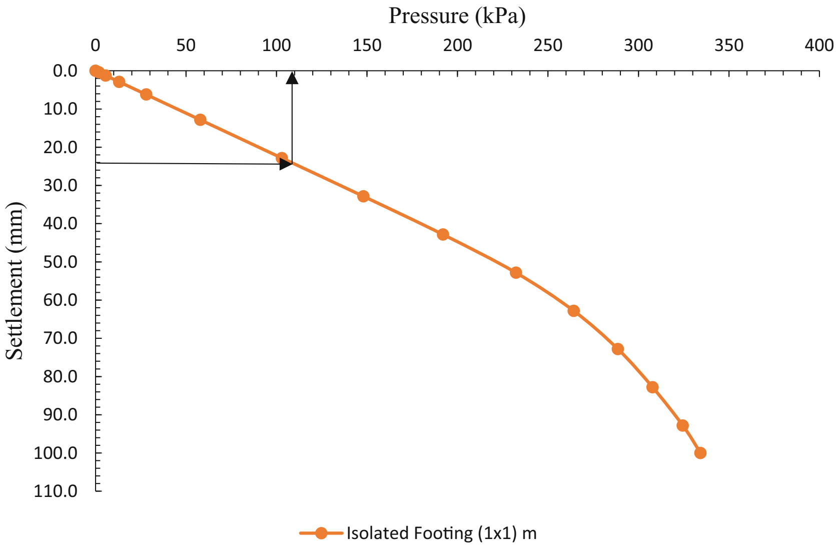

Fig. 1. Load-settlement relationship of the isolated footing.

In this study, three sets of foundations were modelled, i.e., 10 × 10 m^2, 15 × 15 m^2, and 20 × 20 m^2, every set of the foundation was modelled with three different footing design thicknesses of (0.4, 0.6, and 1 m) for a vertical designing load of 24000 kN (multistoried building). All models were developed to simulate and capture the failure behaviour of the soil medium. Soil geotechnical properties were considered homogeneous (constant) within an area of 100 m^2. By considering the symmetry of the footing area about the vertical line (z) through the centre of the footing, a quarter domain is employed, as shown in Fig. 2. The chosen domain of the proposed raft foundation (10 × 10 × 0.4 m^3) and the stress boundary conditions with the deformation mesh are shown in Fig. 3.

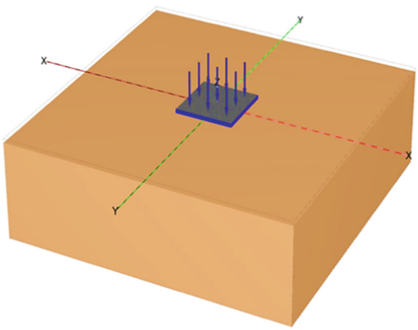

Fig. 2. Finite element model for simulating full footing dimensions (10 × 10) m^2.

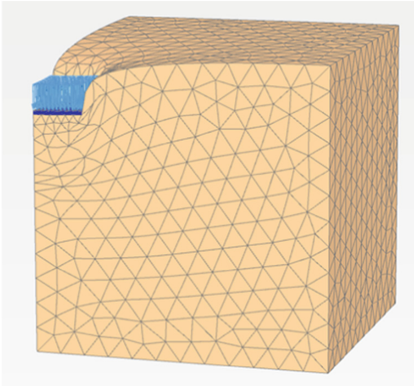

Fig. 3. Deformed mesh of proposed raft foundation (10 × 10 × 0.4) m^3.

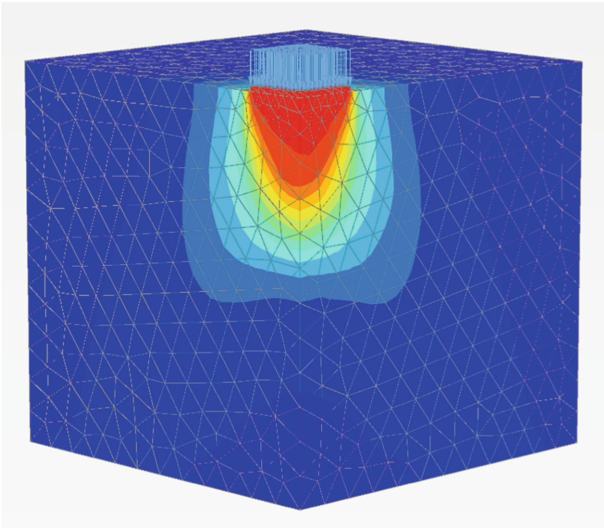

Fig. 4. Settlement simulation by Plaxis 3D of proposed raft foundation (10 × 10 × 0.4) m^3.

For the numerical calculations process, the selected node was chosen at the center of the flat rigid footing assuming that the applied vertical load was uniform, and subsequently the corresponding settlement was considered uniform. Settlement simulation by Plaxis 3D of proposed raft foundation (10 × 10 × 0.4) m^3 is displayed in Fig. 4, and the load-multiplier vs. settlement curve is presented in Fig. 5. Based on the numerical prediction, the indicated load-settlement curves for the center of modeled footings

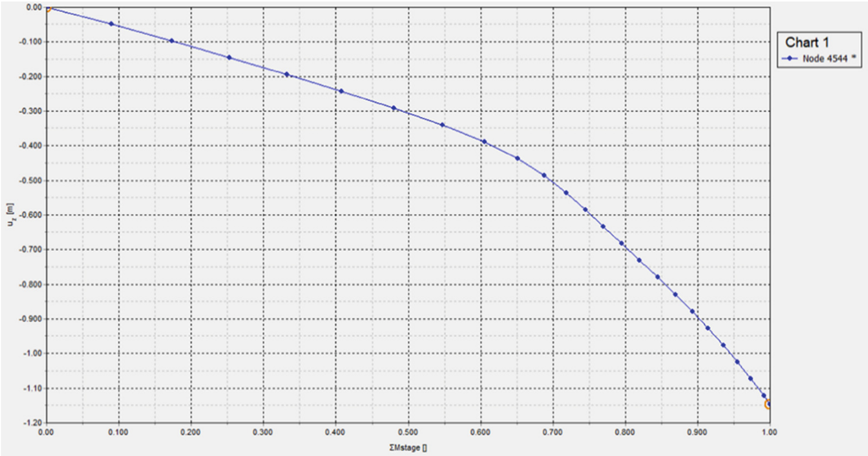

Fig. 5. Load-multiplier vs. settlement curve of proposed raft foundation (10 × 10 × 0.4) m^3.

are presented in Figs. 6, 7 and 8. These figures showed the pressure and the total settlement relationships of the modeled foundations at the peak load value. Generally, as summarized in Table 3; this construction site exhibits high settlement values due to the applied construction loads. If the mat exceeds the limit values of the settlement; a larger foundation area can be adopted in order to achieve lower soil contact pressures.

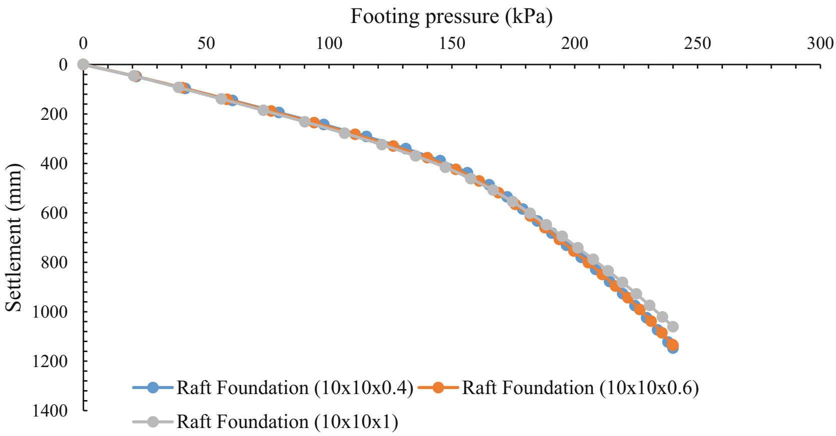

Fig. 6. Load-settlement curves of raft foundation (10 × 10) m^2 with different thicknesses.

The size effect of the raft foundation on the soil's ultimate bearing capacity was well simulated by Plaxis 3D. The obtained results from the numerical modeling as presented in Table 3 demonstrated that the settlement decreases with increasing footing size (B × L). This comes due to the fact that the area of load distribution increases and the effect of the pressure on the footing surface decreases. Thus, increasing the footing area

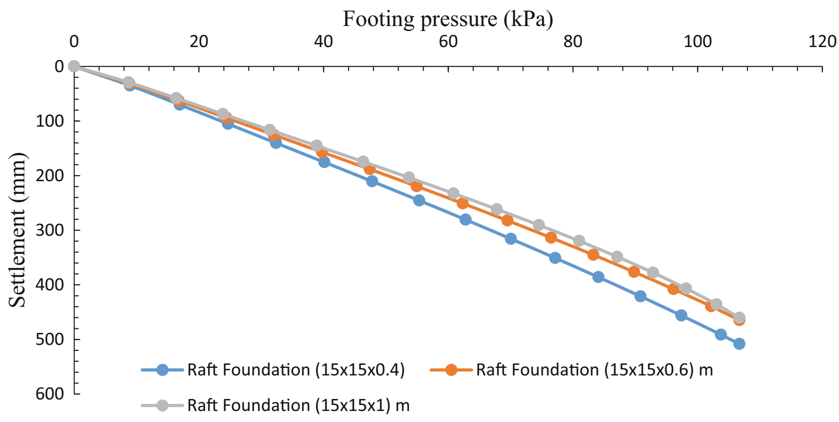

Fig. 7. Load-settlement curves of raft foundation (15 × 15) m^2 with different thicknesses.

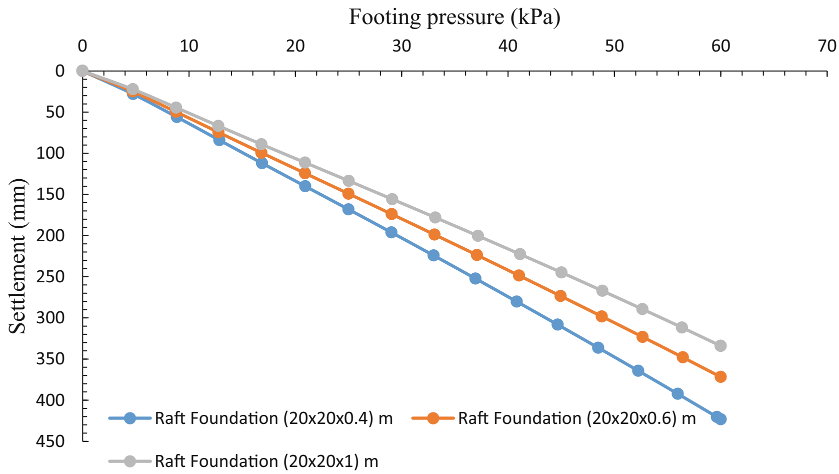

Fig. 8. Load-settlement curves of raft foundation (20 × 20) m^2 with different thicknesses.

Table 3. Settlement values for the proposed shallow foundation models.

Applied pressure (kPa)	240			106.7			60		
Foundation area dimensions (m^2)	**10 × 10**			**15 × 15**			**20 × 20**		
Foundation thickness (m)	0.4	0.6	1	0.4	0.6	1	0.4	0.6	1
Settlement value (mm)	1147	1136	1160	508	465	460	423	372	334
Foundation size increasing ratio (%)	-	-	-	50	50	50	100	100	100
Settlement decreasing percentage (%)	-	-	-	55.7	59	60.3	63.1	67	71.2

will provide an additional factor of safety to the soil bearing capacity. For the presented case study, increasing the footing dimension size with a ratio of 50% will decrease the settlement values with percentages of 55.7, 59 and 60.3% for the foundation thicknesses of 0.4, 0.6 and 1 m respectively. In addition, increasing the footing dimension size with a ratio of 100% will decrease the settlement values with percentages of 63.1, 67 and 71.2% for the foundation thicknesses of 0.4, 0.6 and 1 m respectively.

Furthermore, for load-settlement curves of the raft foundation (10 × 10 m^2) are presented in Fig. 6. It was observed that increasing the foundation thickness had no significant effect on the elastic deformation (elastic settlement) within the soil medium. Figures 7 and 8 show that the settlement values calculated for the foundations of greater thickness were slightly lower than those computed for the smaller thickness. Moreover, by comparing the obtained load-settlement curves from the proposed models' analysis; the larger foundation showed lower settlement values. The achieved settlement curve of the smaller foundation area tends to increase sharply, while the larger foundation settlement curve is increased in a semi-flat manner. Another comparison study was conducted adopting the calculation concept of the allowable settlement of 50 mm beneath each size of the three modelled foundation (of the same thickness of 0.6m). The variation of the load-settlement behavior with respect to the same thickness size from the numerical analysis is shown in Fig. 9.

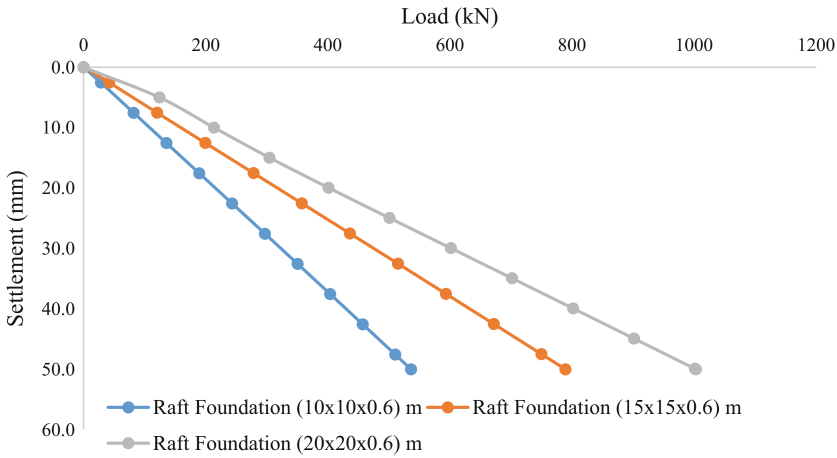

Fig. 9. Comparison of load-settlement response between (a) 10 × 10 m^2 foundation; (b) 15 × 15m^2 foundation; (c) 20 × 20 m^2 foundation according to the design of allowable settlement of 50mm.

In the multistoried building, heavily-loaded shallow foundations resulted in more footing settlement, mainly relying on the soil properties. Figure 9 shows that the foundation with the larger area can support a bigger design load with less soil settlement. As summarized in Table 4, results reveal that the raft foundation of area (10 × 10 m^2) can support only 536.62 kN of load for the corresponding settlement of 50mm, while the foundations of area (15 × 15 m^2) and (20 × 20 m^2) can support 789.60 and 1003.45 kN respectively.

Table 4. Allowable load and pressure according to the design of allowable settlement of 50 mm.

Foundation size (m^2)	10 × 10	15 × 15	20 × 20
Allowable designing settlement (mm)	50	50	50
Allowable designing load (kN)	536.62	789.60	1003.45
Allowable Pressure (kPa)	21.46	14.03	10.03

These proposed models of shallow foundations demonstrate the capability to simulate the load-settlement responses of footings to the applied loads. Additionally, models developed by Plaxis 3D software for shallow foundations on fine-grained soil under vertical loading provide a simple and efficient tool for footing settlement prediction in a realistic manner. The mentioned load-settlement relations for various thicknesses of footing previously are nearly the same for all models with the same area within the elastic deformation zone. However, according to the geotechnical conception, the influential foundation area (width and length) should be realized. The foundation area plays the major role in supporting the structural load applied on the footing. In spite of the parameter of footing thickness, which has less influence on the distribution of the vertical load, the importance of the thickness of the foundation is efficient in construction considerations.

The results indicated that acceptable settlement values are not the only influential factors in geotechnical engineering design; as the results indicated that the influential factors include, but are not limited to: (a) local soil geotechnical properties, (b) the soil ultimate bearing capacity, (c) the design load, and (d) the construction type and quality) can work together in a different direction to produce the appropriate preventative design that satisfies safety aspects. Furthermore, the variation in soil properties affects the process of selecting the proper type of foundation. If the soil bearing capacity (ground support) is insufficient, the piles' system should be considered. In this instance, special attention should be paid to the loads acting on the piles, and the mechanism of load transfer from the structural building onto the piles.

7 Conclusions

The achieved outcomes of this study yielded in the following conclusions:

- As the soil settlement is a significant factor in engineering design and modeling soil-structure interaction, the utilised models simulated with Plaxis 3D have reasonably predicted the load-displacement of the soil layer affected by large-scale footing response.
- The used software for finite element analysis can successfully estimate the soil's ultimate bearing capacity and corresponding settlement relationship with notable accuracy and saving time and energy.
- For the presented case study, increasing the footing dimension size with a ratio of 50% will decrease the settlement values with percentages of 55.7, 59 and 60.3% for

the foundation thicknesses of 0.4, 0.6 and 1 m respectively. In addition, increasing the footing dimension size with a ratio of 100% will decrease the settlement values with percentages of 63.1, 67 and 71.2% for the foundation thicknesses of 0.4, 0.6 and 1 m respectively.

- The Plaxis 3D is considered to be strongly capable of simulating the analysis and design of large-scale shallow foundations and further work.

Acknowledgement. The authors are grateful to thank Mr. Soran Ibraheem Muhammed for his support and help for field visits and all the supplement of the related tests results.

References

1. Holtz, R.D.: Stress distribution and settlement of shallow foundations. In: Fang, H.Y. (eds): Foundation Engineering Handbook. Springer, Boston, MA; (1991). https://doi.org/10.1007/978-1-4615-3928-5_5
2. Das, B.M.: Principles of Foundation Engineering, SI, 7th edn. Cengage Learning, USA (2011)
3. Das, B.M., Sivakugan, N.: Settlements of shallow foundations on granular soil: an overview. Int. J. Geotechnical Eng. J. Ross Publishing, Inc. **1**(1), 19–29 (2007)
4. Kempfert, H., Gebreselassie, B.: Shallow foundations on soft soils. In: Excavations and Foundations in Soft Soils. Springer, Berlin, Heidelberg; (2006). https://doi.org/10.1007/3-540-32895-5_5
5. Al-Taie, E., Al-Ansari, N., Knutsson, S.: Effect of bearing capacity on designing foundations in Iraq using STAAD Pro-v8i Engineering, **6**, pp. 292–303 (2014)
6. Azeez, S.N.: Classification of Serwan river Levee's Soils in Kurdistan Region- Iraq, J. Garmian University, December; 4(4), 115 (2017)
7. Muhaimeed, A.S., Saloom, A.J., Saliem, K.A., Alani, K.A., Muklef, W.M.: Classification and distribution of Iraqi soils. Int. J. Agric. Innov. Res. **2**(6), 997–1002 (2014)
8. Issazadeh, L., Umar, M.I., Al-sulaivany S.I., Hassanpour. J.: Geostatistical analysis of the permeability coefficient in different soil textures. Contemporary Agriculture **67**(2), 119–124 (2018)
9. Rate, A.W., Sheikh-Abdullah, S.M.: The geochemistry of calcareous forest soils in Sulaimani Governorate, Kurdistan Region. Iraq. Geoderma. **289**, 54–65 (2017)
10. Khorshid, M.S.H., Thiele-Bruhn, S.: Contamination status and assessment of urban and non-urban soils in the region of Sulaimani City, Kurdistan, Iraq. Environmental Earth Sciences **75**(16), 1–15 (2016). https://doi.org/10.1007/s12665-016-5972-z
11. Bapeer, G.B., Muhammad, R.K., Nadr, K.A., Khodakarami, L., Al-Ansari, N.: Geotechnical properties of soil in Ranya and Arbat Area, Sulaimaniya, Kurdistan Region, Iraq. Journal of Earth Sciences and Geotechnical Eng. **10**(5), 35–48 (2020), ISSN: 1792–9040 (print version), 1792–9660 (online)
12. Najmaddin, P.M., Salih, N.B., Abdalla, T.A.: Evaluating the spatial distribution of some soil geotechnical properties using various interpolation methods (Case Study: Sulaimani Province, Iraq). J. of Soil Sciences and Agricultural Engineering, Mansoura Univ. **11**(7), 275–281 (2020)
13. Rashed, K.A., Salih, N.B., Abdalla, T.A.: Correlation of consistency and compressibility properties of soils in Sulaimani city. Sulaimania Journal for Engineering Sci. **4**(5) (2017)
14. Abdalqadir, Z.K., Salih, N.B. and Salih, S.J.H.: Using steel slag for stabilizing clayey soil in Sulaimani City-Iraq. J. Engineering **26**(7), 145157 (2020)

15. Salih, N.B., Abdalla, T.A.: The effect of freeze-thaw cycles on the geotechnical properties of clayey soil treated with lime. J. Duhok Univ. **23**(2), 454–463 (2020)
16. Chao, K.C., Nelson, J.D.: Validation of foundation design method on expansive soils. Geotechnical Engineering Journal of the SEAGS & AGSSEA, 1 March, Vol. 50 No. ISSN 0046–5828 (2019)
17. Bowles, J.E.: Foundation Analysis and Design. 5th ed. The McGraw-Hill Companies, Inc., ISBN 0–07–912247–7 (1996)
18. Venkatramaiah, C.: Geotechnical Engineering. 3rd ed.New Age International (P) Ltd., Publishers, ISBN (10) : 81–224–2338–8 (2006)
19. Wang, X., Schmettow, T., Chen, X., Xia, C.: Prediction of ground settlements induced by twin shield tunnelling in rock and soil – A case study, Underground Space, ISSN 2467–9674 (2022). https://doi.org/10.1016/j.undsp.2021.12.001. (https://www.sciencedirect.com/science/article/pii/S2467967422000034)
20. Gupta, S., Mital, A.: Numerical analysis of bearing capacity of rectangular footing. J. Phys.: Conf. Ser. 1240 012039 (2019)
21. Waheed, M.Q., Asmael, N.M.: Parametric study of shallow foundation bearing capacity in clayey soil. International Journal of Civil Engineering and Technology (IJCIET) **9**(10), 1223–1230 (2018). http://iaeme.com/Home/issue/IJCIET?Volume=9&Issue=10
22. Salimath, R.S., Pender, M.J.: Moment-rotation behavior of shallow foundations with fixed vertical load using PLAXIS 3D. In: 6th International Conference on Earthquake Geotechnical Engineering. 1–4 November, Christchurch, New Zealand (2015)