Numerical Modelling Observations of Settlement for Pad Footings Supported on Soft Clay Soil

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Abstract. Settlement calculation is an important part in the design of shallow foundations resting on soft soils. The size of the foundation, the depth of the footings, and the rise in ground water level are thought to influence settlement and have been the subject of much research for many years. Thus, this study compared several pad footing sizes using numerical techniques as the basis. The first objective of this study was to analyse soil and pad footing settlement, and to determine the optimal size of footing that withstands excessive settlement due to variation in the water table and the depth of the foundation. Three footing embedment depths of 1.5, 2, and 3 m with three water table positions, at the GL (0 m), 1.5, and 3 m with an applied foundation concentrated load of 440 kN using five footing models of 1.5mx1.5m, 2mx1.5m, 2 m x 2 m, 2.5x1.5m, and 2.5x1.5m pad footing with a uniform thickness of 0.5 m were considered. In this study, a 3D Plaxis simulation is used for predicting the settlement of shallow foundations on soft clay soils. Settlement results were discovered at various water table positions and foundation depths. The study found that the 2.5x2m footing was deemed the best among the simulated foundations, and the 3 m foundation embedment was considered the best at shallow depths due to less excessive settlement than the other tested foundations. The settlement had a significant impact on the size of the foundation and the depth of the footing. The depth of the water table has a small impact on the settlement. Parametric analysis is also being used to gain a better understanding of the behaviour of the elastic settlement of various shallow foundations. It is found that the footing area increases, settlement decreases and vice versa.

1. Introduction

A foundation is one of the main building components that transfers the structure's load to the ground. When designing a foundation, it is necessary to examine the type of soil, its behaviour, as well as its settlement and bearing capacity. The foundation is a key element in design and construction. To avoid soil failure, it is essential to ensure that the load distribution on the soil is adequate. A foundation is important because it serves as the contact between a structure's load-bearing components and the ground. Two types of foundations exist. There are two types of foundations: shallow foundations and deep foundations. To provide for adequate load distribution, the size and kind of the foundation should be precisely calculated. The increased size of the footing relative to the column support results in an increased area of contact between the footing and the soil [1]. Settlement is an essential parameter in the design of the pad footing, particularly when the footing width exceeds one meter. Excessive settlements can result in serviceability issues, making settlement a more crucial parameter to consider when designing foundations than the bearing capacity of the soil [2]. Locally and internationally, the number of project failures due to soil settlement and structural deformation has grown. Several of the
failures were attributed to the soft soil's poor shear strength and excessive compressibility. Settlement may be considered as the downward movement of the ground in the soil as a result of applied pressures. As a result of soil settlement, the load carrying system will be change. The masonry buildings are relatively intolerant of settlement and may undergo structural instability (cracking) when angular distortions exceed 1/300. In practice, bearing stresses are generally limited to a maximum of 25 mm (1 in) of total settlement and roughly half of the total settlement as differential settlement [3]. The research focuses on numerical analysis through the PLAXIS 3D software. The Finite Element Method (FEM) is a numerical analysis technique for theoretical systems that transforms the continuous into a finite structure comprised of a finite number of units and then analyses the stress and deformation of each unit [4]. A 3D finite element mesh is produced from this geometry. Boreholes are used to define soil strata. Horizontal work planes were used to define structures. [5]. Plaxis 3D performs calculations and outputs the results in animation and/or numerical form using its calculating features [6]. Construction on soft soils is a significant problem in the field of geotechnical engineering. The settlement of five different footing sizes will be evaluated in this study, and the data will be examined to identify the settlement behaviour of pad footings resting on soft clay, as well as the optimum dimension of Pad footing on soft Clay. This study helps to perform analysis of settlement of different sizes of pad footings on soft clay soil beds using PLAXIS 3D software. The importance of this study is to provide the optimum size of the pad footing with the best depth of the foundation in a soft clay bed. In soils with a high compressibility, significant settlement and compression will occur, and these values will likely exceed acceptable limits, resulting in serious damage to the building. Accurate settlement prediction is important because settlement, rather than bearing capacity, typically determines foundation design. The outcome of this study will contribute knowledge about the settlement behaviour of pad footings of various sizes, depths, and water table positions; the importance of knowing the proper size of footing and depth of foundation results in the use of an appropriate amount of concrete in the foundation and the reduction of foundation trench excavation, which contributes to the economy. The importance of this research is to apply or use the effectiveness of geotechnical design throughout the design process in order to ensure the structure's stability. Other researchers may be able to apply the findings from this study to conduct future research that will have a significant influence, particularly in the geotechnical sector. As a result, it predicted settlements with a variety of footing sizes, water table positions and foundation depths. This study will help designers in predicting settlement for future projects. This research will provide the importance of pad foundation size selection.

2. Methodology

This study used soft clay soil, it emphasizes the application of the Mohr Coulomb models of soil behaviour. The soil characteristics used in this study are taken from the properties of soft clay soil based on previous research done by [7], the study investigated a bearing capacity of the gravelly sand column, installed in soft clay bed. The soil properties was given in table 1.

2.1. Numerical analysis

Plaxis 3D was used to conduct the numerical study of foundation settlement. Plaxis 3D uses index, elastic, and strength characteristics as input data. It produces unstructured three-dimensional finite element meshes with the ability to adjust the mesh globally or locally. Plaxis 3D connect performed calculations and outputs the results.

Table 1. Properties of soft soil [7].

| Properties                | Unit       | Soft Clay |
|---------------------------|------------|-----------|
| Specific gravity          | .............| 2.65      |
| Moisture content          | %          | 42        |
| Un-drained shear strength | kPa/ kN/m2 | 15        |
| Cohesion                  | KN/m2      | 8.87      |
Angle of internal friction $\phi$ 31.2
Dilatancy angle $\psi$ 10.4
Permeability m/day 0.0006048
Young modulus KN/m$^2$ 1800
Poisson ratio .................. 0.35
Unit weight saturation KN/m$^3$ 17.38
Unit weight unsaturation KN/m$^3$ 12.24

The three-dimensional finite element program PLAXIS is used to simulate pad foundations to determine the settlement. During the modelling in PLAXIS, various trial analyses were performed to assess the model behaviour. The variation in strength parameters 'c' and $\phi'$ done since the settlement of a soil depends on strength parameters. To carry out a finite analysis using PLAXIS, a finite element mesh was created and the material properties and boundary conditions were specified. To set up a FEM, a geometry model composed of points, lines, and other components was created in the XYZ-space for PLAXIS 3D. The finite element mesh was generated in PLAXIS 3D after the material properties and boundary conditions are assigned. The Mohr-Coulomb failure criteria was used to model the foundation clay soil as an isotropic elastic-perfectly plastic material. The Plaxis programme inputs the constitutive parameters for clay soils, which include the un-drained shear strength (C), un-drained elastic modulus (E), poison ration (v), and bulk unit weight ($\gamma$). The FEM analysis is done with Plaxis 3D numerical application. Soil limits are $X_{\text{min}} = 0$ m, $X_{\text{max}} = 10$ m, $Y_{\text{min}} = 0$ m and $Y_{\text{max}} = 10$ m, $Z_{\text{min}} = 0$ m and $Z_{\text{max}} = 10$ m respectively. The footings were placed at the centre of soft clay boundaries in X-Y plane with varying depths and water table positions.

2.2. Structural geometry parameters

The dimensions of the footings were taken as assumptions. They are rectangle, square shapes. The Pads used in this project are concrete pads, therefore, table 2 below indicated some characteristics of concrete that needed for the Plaxis software input during the model's simulation including concrete density, modulus of elasticity, poisons ratio, and shear modulus.

| Geometry parameters (Assumption) | Material Property [8]. |
|----------------------------------|-------------------------|
| Footing Shape | Footing Dimension (LXB) in (m) | Thickness (m) | Density of material $\gamma$(KN/m$^3$) | Elastic Modulus E, (KN/m$^2$) | Poisson’s Ratio. | Shear Modulus, G (KN/m$^2$) |
| Square | 1.5x1.5 | 0.5 | 24 | $3 \times 10^7$ | 0.2 | $1.25 \times 10^7$ |
| Rectangle | 2.0x1.5 | 0.5 | 24 | $3 \times 10^7$ | 0.2 | $1.25 \times 10^7$ |
| Square | 2.0x2.0 | 0.5 | 24 | $3 \times 10^7$ | 0.2 | $1.25 \times 10^7$ |
| Rectangle | 2.5x1.5 | 0.5 | 24 | $3 \times 10^7$ | 0.2 | $1.25 \times 10^7$ |
| Rectangle | 2.5x2.0 | 0.5 | 24 | $3 \times 10^7$ | 0.2 | $1.25 \times 10^7$ |

2.3. Load

After completely defining the geometry, the load used in this study was calculated for a light-weight mono-family house consists of one floors and has a spread type of foundation resting on a soft clay soil shown in Figure 1. The calculated load was 440KN. The thickness of the spread foundations is 0.5 m each, and the foundation is applied vertically to the center of the footing.
3. Result and discussion

The finite element program PLAXIS 3D connected version, it is used to perform an analysis of pad footing on a clay bed. The results of the numerical analysis of five footings applied to a vertical load of 440kN at three different foundation depths and at three water table positions are presented in this section, along with a discussion of the findings. The numerical simulated results of five footing models of size 1.5x1.5m, 2x1.5m, 2.5x1.5m, 2x2m, and 2.5x2m at three different foundation depths (1.5m, 2m, and 3m below ground level) with three water table positions (GL, 1.5m, and 3m). The analysis and discussion of each footing model were taken separately.

3.1. Model size 1.5mx1.5m

The Model 1.5x1.5m was simulated 9 times with different water table positions and foundation embedment. The table 3 presented settlement results of 1.5x1.5m footing at foundation depth of 1.5m below GL and the water table position on GL, and foundation embedded 1.5m below ground level. The whole results of the models was presented in table 3.

Table 3. Settlement result for 1.5x1.5m footing.

| Model size | Settlement (m) | \(D_f = 1.5m\) | \(D_f = 2m\) | \(D_f = 3m\) |
|------------|----------------|----------------|----------------|----------------|
| 1.5 x 1.5m | \(U\) | \(W_t = 0m\) | \(W_t = 1.5m\) | \(W_t = 3m\) | \(W_t = 0m\) | \(W_t = 1.5m\) | \(W_t = 3m\) | \(W_t = 0m\) | \(W_t = 1.5m\) | \(W_t = 3m\) |
| \(U\) | m | m | m | m | m | m | m | m | m |
| Min | =7.563x1 | 6.956x1 | 6.956x1 | 6.956x1 | 6.956x1 | 6.956x1 | 6.956x1 | 6.956x1 | 6.956x1 |
| Max | =7.541X | 7.415X | 7.415X | 7.415X | 7.415X | 7.415X | 7.415X | 7.415X | 7.415X |
| Min | 0.04575 | 0.03748 | 0.03983 | 0.03728 | 0.03983 | 0.03728 | 0.03983 | 0.03728 | 0.03983 |
| Max | 0.04353 | 0.03748 | 0.03983 | 0.03728 | 0.03983 | 0.03728 | 0.03983 | 0.03728 | 0.03983 |

Figure 1. Column plan.
As shown in the result of table 3, the total settlement result of models with a depth of foundation 1.5m below GL, the greater displacement found is 46.64mm which is when the WT on GL. When WT lied on GL, the maximum total settlement of the depth of the foundation 2m below GL was 39.85mm. The total settlement of foundation depth of 3m is 34.72mm. The results show that the total settlement is always greater than the water table on GL in all three cases, and that the total settlement decreases sequentially with foundation depth. The settlement results from the various embedment show that increasing the depth of the foundation reduces the amount of settlement.

3.2. Model size 2mx1.5m
The Model 2x1.5m was modelled 9 times, with varying water table locations and foundation embedment, to look the depth of foundation, and water table impact on settlement. The results were presented in table 4.

Table 4. Settlement result for 2x1.5m footing.

| Model size | Settlement (m) | Df = 1.5m | Df = 2m | Df = 3m |
|------------|----------------|------------|------------|------------|
|            | W_T = 0m | W_T = 1.5m | W_T = 3m | W_T = 0m | W_T = 1.5m | W_T = 3m | W_T = 0m | W_T = 1.5m | W_T = 3m |
| 2x1.5m     | UZ          |            |          |            |            |          |            |          |            |          |
|            | 0.04061 | 0.03987 | 0.03959 | 0.02821 | 0.02654 | 0.02715 | 0.02840 | 0.02701 | 0.02676 |
|            | Min = 10^-3m | Max = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m |
|            | Max = -0.0006 | Min = -0.0001 | Max = -0.0003 | Max = -0.0002 | Max = -0.0001 | Max = -0.0001 | Max = -0.0001 | Max = -0.0001 | Max = -0.0001 |
|            | Min = 0.0001 | Max = 0.0001 | Min = 0.0001 | Min = 0.0001 | Min = 0.0001 | Min = 0.0001 | Min = 0.0001 | Min = 0.0001 | Min = 0.0001 |
|            | m | m | m | m | m | m | m | m | m |

The largest displacement discovered is 40.61mm when the WT is laid on GL, as indicated in table 4, the overall settlement result of models with a foundation depth of 1.5m below GL. When WT is laid on GL, the maximum total settlement of the depth of the foundation 2m below GL is 28.21mm. The total settlement at a depth of 3 meters is 28.40 millimetres. The total settlement is always greater when the water table is at GL in all three situations, and it also indicates that the total settlement decreases with the foundation depth.

3.3. Model size 2.5mx1.5m
To explore the depth of foundation and the effect of water table depth on settlement, the model was run 9 times, every instance adjusting the water table location and foundation embedment. Table 5 displayed the settlement outcomes.

Table 5. Settlement result for 2.5x1.5m footing.

| Model size | Settlement (m) | Df = 1.5m | Df = 2m | Df = 3m |
|------------|----------------|------------|------------|------------|
|            | W_T = 0m | W_T = 1.5m | W_T = 3m | W_T = 0m | W_T = 1.5m | W_T = 3m | W_T = 0m | W_T = 1.5m | W_T = 3m |
| 2.5x1.5m   | UZ          |            |          |            |            |          |            |          |            |          |
|            | 0.03448 | 0.03374 | 0.0336 | 0.02820 | 0.02662 | 0.02714 | 0.02416 | 0.02310 | 0.02297 |
|            | Min = 10^-3m | Max = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m | Min = 10^-3m |
|            | Max = -0.000 | Max = -0.000 | Max = -0.000 | Max = -0.000 | Max = -0.000 | Max = -0.000 | Max = -0.000 | Max = -0.000 | Max = -0.000 |
|            | Min = 0.000 | Max = 0.000 | Min = 0.000 | Min = 0.000 | Min = 0.000 | Min = 0.000 | Min = 0.000 | Min = 0.000 | Min = 0.000 |
|            | m | m | m | m | m | m | m | m | m |
The total settlement result of models with a depth of foundation of 1.5m below GL, as shown in table 5. The greatest displacement discovered is 33.74 mm, which is when the WT lies at 1.5m below GL. When WT is laid on GL, the maximum total settlement of the depth of the foundation at 2m below GL is 28.20mm. The total settlement for a 3m foundation depth is 24.16mm which is acceptable and safe structure. The results always demonstrate that the total settlement is greater when the water table on GL is higher in all three situations, and it also shows that the total settlement decreases sequentially with foundation depth.

3.4. Model size 2mx2m
To verify that the water table, and foundation depths had an influence on the settlement, the model was constructed 9 times, using various water table locations and foundation embedment, the settlement results presented in table 6.

| Mode size (m) | Settled ment (m) | DF = 1.5m | DF = 2m | DF = 3m |
|--------------|-----------------|-----------|---------|---------|
|              | WT = 0m | WT = 1.5m | WT = 3m | WT = 0m | WT = 1.5m | WT = 3m | WT = 0m | WT = 1.5m | WT = 3m |
| 2x2m | [U] 0.03356 | 0.03139 | 0.03032 | 0.02823 | 0.02654 | 0.02715 |
|        | Min = -0.195 | Max = 0.132 | Max = 0.103X1 | Min = -6.573X1 | Min = -6.272X1 | Min = -6.190X1 |
|        | 0.0242 | 0.03178 | 0.03156 | 0.02822m | 0.02647 | 0.02709 |
|        | Min = - | Min = - | Min = - | m | m | m |

As seen in table 6, the overall settlement result of models with a foundation depth of 1.5m below the GL is 33.56mm. That's when the WT is on the GL. When the WT lies on the GL, the maximum total depth of the foundation is 28.23mm below the GL. The overall depth of the base settlement is 23.50mm. When the water table in all three situations indicates GL, the total settlement is always greater, and it illustrates that the total settlement decreases with the foundation depth.

3.5. Model size 2.5mx2m
Table 7 demonstrates the 9 model findings with different foundation depths and water table position.

| Model size (m) | Settlem ent (m) | Df = 1.5m | Df = 2m | Df = 3m |
|---------------|-----------------|-----------|---------|---------|
|               | WT = 0m | WT = 1.5m | WT = 3m | WT = 0m | WT = 1.5m | WT = 3m | WT = 0m | WT = 1.5m | WT = 3m |
| 2.5x2m | [U] 0.02876 | 0.02828 | 0.02823 | 0.02434 | 0.02308 | 0.02366 |
|        | Min = -6.989X1 | Max = 6.930X1 | Max = 6.867X1 | Min = -6.367X1 | Min = -5.894X1 | Min = -5.912X1 |
|        | 0.02752 | 0.02700 | 0.02697 | 0.02431 | 0.02278 | 0.02332 |
|        | Min = - | Min = - | Min = - | m | m | m |

The entire settlement results in models with a depth of foundation of 1.5m below GL, as shown in table 7. When the WT is on the GL (0m), the displacement is 28.76 mm. The maximum total
settlement of the depth of the foundation at 2m below GL is 24.34mm. The overall settlement for a 3m foundation depth is 20.11mm. The results always demonstrate that the total settlement in case of depth of foundation was 1.5 is greater than the allowable settlement of 25mm. However, in the cases of 2m and 3m depth of foundation, the settlement results found were always less than 25mm. Therefore, when the water table on GL is higher in all three situations, it also shows that the total settlement decreases sequentially with the foundation depth.

3.6. Effect of footing size on settlement

Figure 2 gives typical area-settlement relationships for footings of different widths on the surface of a clay soil property. It can be seen that the area of size footings increase with the decrease in the settlement of the footings. However, the relationship indicated that the area of footing is significant for reduction of settlement.

![Area of footing vs. Settlement](image_url)

**Figure 2.** Area of foundation-Settlement curve.

3.7. Effect of depth of embedment on settlement

The depth of the footing is a key factor in determining how much the soil will settle. In this study, the effect of increasing the embedment depth on total settlement under a concentrated load was investigated, and the embedment depth of the foundation was increased from 1.5 to 3 metres, as shown in figures 3. It can be shown that the maximum total settlement reduces as the embedment depth increases for all of the footing sizes under consideration in this study. These findings are in agreement with those of [9], and [6] who found that embedding results in a significant decrease in settlement. Consequently, based on the simulation results, it appears that the foundation embedment has a positive effect on the foundation's ability to reduce settlement for all of the foundation sizes considered in this study.
3.8. Effect of water table on settlement

The water table influence on settlement was determined by measuring settlements at various water table depths. In figure 4, it can be shown that the water table has a very small effect on settlement, and as a result, it does not have a positive significant impact on settlement for the types of footing investigated in this study.

![Figure 3. Settlement-depth of foundation.](image)

![Figure 4. Settlement-water table.](image)

3.9. The optimum footing

The five models were simulated 45 times in this study. Each footing was assessed nine times, three foundation depths and three water table positions were investigated, and settlement results were compared; smaller models of 1.5x1.5 and 2x1.5m failed in all cases when compared to the allowable settlement specified by [10]. Despite the fact that footings of 2.5x1.5m and 2x2m could withstand the structure's load to a depth of 3m. While the 2.5x2m footing, like all other footings, failed partially at 1.5m depth but could support the load at 2m and 3m depth, the maximum settlement at 2m depth was 24.34mm when the water table was at GL. The maximum settlement was determined to be 19.16mm for a 3m foundation depth. However, the settlement result at the 2m and 3m foundation embedment depths was acceptable in accordance with [11], which specifies a maximum settlement of 25mm. Thus,
among the simulated models, the optimal footing was a 2.5x2m footing at 2m and a 3m foundation depth. The results presented in this paper is in accordance to the theories related to foundation engineering, where larger area of footing provide better stability. However, this study has laid a clear indication on the range of parameters that can be easily predicted with numerical analysis.

4. Conclusion
The Determination of the settlement of a pad foundation resting on soft clay, a series of numerical analyses was performed. Various settlements were found at varying water table depths, and each instance then received a varied foundation depth. In order to estimate the foundation settlement, a finite element analysis was performed using the PLAXIS 3D Connect. By using the Mohr Coulomb model, the analyses were performed. The following findings were obtained as a result of the research conducted:
1. Due to less settlement than the other footings, the 2.5x2m footing was determined to be the optimal footing among the five evaluated footing types. The depth of 3m proved to be the most successful.
2. The depth of the water table have a small impact on settlement.
3. The different size of footing gives different settlement results. It should also be noted that footing area increase, settlement decreases and vice versa.
4. The depth of embedment have noticeable influence on settlement.
5. The simulation takes less time when all essential data is available, it might be beneficial for gaining an understanding of the soil-structure interaction behaviour.
6. The study's findings can be used to the design of lightweight single-story structures.

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