Numerical Modeling of Shallow Foundation Behavior Using Soft Soil Model

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Abstract: This study discusses the results of simulation a finite element analysis of the load-settlement curve using soft soil model of shallow foundation subjected to axial load rested on three different types of clayey soils, it was considered different shear strength parameters (C=16, C=25, and C=70). It was concluded for clayey soil of C=16, there was a match to the experimental load–settlement curve using the soft soil model. It was also observed increase in the foundation width led to an increase in bearing capacity, however, bearing capacity increased by around (79 %) for an increase in footing width of (6.25), so it was about (144%) for (12.5).

1. Introduction
The part of a structure that conveys the structure's load to the soil is called the foundation. It's essential to understand the type of soil, it behaves, and how much loads it can support when designing a footing. The footing should be constructed in such a way that the applied stress on the soil is less than its capacity. A shear failure may occur if the soil is overstressed, causing the soil to slide from beneath the structure and causing failure. As a result, determining the load-bearing capacity of the footing is the first and most important stage in the footing design process [1].

The PLAXIS-3D (V.20) program is a useful tool for describing and assessing soil behavior and settlement when subjected to vertical loading. The stress-strain relationship of a specific material is represented by a constitutive model in finite element methods, which models the behavior of soil in a single element.

The Soft Soil model is ideal for simulating the behavior of soft and compressible soils like clay and peat, and the Soft Soil model is perfect for simulating the behavior of soft and compressible soils like clay and peat. [2].

2. Finite Element Mesh and Boundary Condition
One of the most acceptable numerical approaches is the finite element technique (FEM). It was utilized for acquiring a rough answer for complex issues in different fields of engineering [3]. PLAXIS-3D (V.20) Software used to implement a finite element analysis. The constitutive model of the soil is the Soft Soil Model (SSM). The footing is considered as linear elastic. The properties for soil and footing are shown in Table1.
To acquire a precise numerical result, the mesh should be fine enough. On the other hand, very fine mesh should be avoided because it will result in excessive extreme calculation [4]. A medium to fine mesh was chosen for soil and footing in this study. To model and describe the soil, 10-Node tetrahedral elements were used, and a 6-Node plate was used to imitate the behavior of the footing, Figure 1. The geometry of the two footings resting on the cohesive soil is shown in Figures 2 and 3. The geometric model's dimensions were determined based on the criteria, with the ratio as recommended by the PLAXIS-3D (V.20) software tutorial manual [5]. Table 1 clarifies the material properties used for analysis. Three different types of clay soils were used for different shear strength parameters values classified to soft soil \((c=16)\), medium \((c=25)\) approved by the study of Rahil (2007) where the footing was represented as rectangle shape with a dimension of \((200mm \times 400mm)\) \([\text{no. }]\). And a stiff clay \((c=70)\) approved by the study of Waheed & Moutaz (2019), where in this work the shape of footing is square with \((0.8m)\) width \([\text{no. }], 11-13] \).
Figure 2. The geometry model of footing -1 (C=70).

Figure 3. The geometry model of footing -2 (C=25).

Table 1. The input properties of the studied soil. [6], [7]

| Soils types | Soil 1 | Footing | Soil 2 | Soil 3 | Footing |
|-------------|--------|---------|--------|--------|---------|
| Model name  | SSM    | Linear Elastic | SSM    | SSM    | Linear Elastic |
| Type of drainage | Drained | Non-porous | Un Drained A | Un Drained A | Non-porous |
| $(\gamma)$ (KN/m$^3$) | 17 | 78.5 | 20 | 16.5 | 27 |
| $(\gamma_{dry})$ (KN/m$^3$) | 15 | - | 17 | 18.5 | - |
| $c^\prime$ (kPa) | 70 | - | 25 | 16 | - |
| $\phi^\prime$ | 25 | - | 25 | 5 | - |
| $\gamma$ | 0.4 | 0.26 | 0.2 | 0.2 | 0.4950 |
| $\lambda^*$ | 0.05930 | - | 0.087 | 0.044 | - |
| $k^*$ | 0.00579 | - | 0.013 | 0.016 | - |

*Estimated based on correlations [9].

3. The Soft Soil Model (SSM)
The SSM model is a Cam-clay type model that is used to investigate the primary compression pressure of normally-consolidated clayey soils. This model can be used with materials that have a high compressibility, such as normally consolidated clays, clayey silts, and peat. Despite the fact that the Hardening Soil model often replaces the capability modeling of this model, the Soft Soil model is preferable to demonstrate the pressure conduct of very soft soils. For the SSM model, the supposition that is a logarithmic relation subsist in the midst of the volumetric strain, $\varepsilon_v$, and the mean affecting stress, $P'$, the equation for that could be given

$$\varepsilon_v - \varepsilon_v^0 = -\lambda^* \ln \left( \frac{P'}{P_0} \right) \text{(compression)} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1)$$

where:
$\varepsilon_v$: Volumetric strain,
\[ \varepsilon_v^0: \text{Initial volumetric strain}, \]
\[ P': \text{Mean effective stress}, \]
\[ P^0: \text{Initial effective stress}, \]
\[ \lambda^*: \text{Modified compression coefficient}, \]
\[ \lambda^* = \frac{c_c}{2.3(1+e_0)} \] ... (2)
\[ \text{where:} \]
\[ C_c: \text{Compressible coefficient, and} \]
\[ e_0: \text{Initial void ratio} \]

During isotropic unloading and reloading a different path (line) is followed, which can be formulated as:
\[ \varepsilon_v - \varepsilon_v^0 = -\kappa^* \ln \left( \frac{p'}{p_0'} \right) \text{ (unloading/reloading)} \] ... (3)
\[ \text{where:} \]
\[ \varepsilon_v: \text{Elastic volumetric strain}, \]
\[ \varepsilon_v^0: \text{Initial elastic volumetric strain, and} \]
\[ \kappa^*: \text{Modified swelling coefficient}, \]
\[ K^* \approx \frac{2c_s}{2.3(1+e)} \] ... (4)
\[ \text{where:} \]
\[ C_s: \text{Swelling coefficient, and} \]
\[ e_0: \text{Initial void ratio}. \] [3]

The SS model can simulate soil behavior under a general of stress conditions. Nonetheless, for clarity, only triaxial loading circumstances with \((\sigma_2 = \sigma_3)\) are considered.

A yield function \(f\) is depicted in Figure 4 as a circle in the \(p' - q\) plane. Figure 5 depicts the entire yield contour in major stress space.

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**Figure 4.** The yield surfaces of the Soft Soil model: the red line is the Mohr-Coulomb yield surface, and the blue line is the elliptical cap yield surface. [9]
The soft soil model, unlike the Mohr-Coulomb material model, is capable of representing both elastic and plastic material states. It is a more advanced constitutive material model, and the soft soil model's key features are as follows (PLAXIS, 2012):
The primary shortcomings of the soft soil model include [10]:
• Not suitable for soils other than soft states that are ordinarily or close to normally consolidated.
• The creep (secondary consolidation) is not considered.
• Less suitable for stress pathways that aren't compression.
• The anisotropy of the soil is ignored.
• The behavior of failure as per the Mohr-Coulomb requirement.
• The yield surface adapts to a modified Cam clay model with a plastic strain flow rule.
• Oedometer testing is used to determine stiffness parameters.

The soft-soil model has several important advantages:
• Stiffness that is related to stress (logarithmic compression behavior).
• There's a difference between main loading and unloading-reloading.
• Pre-consolidation stress memory.

4. Results and discussions
PLAXIS 3D software was used to conduct the finite element analysis for different clay soil of two types of shallow foundation, their properties are clarified in Table 1. Figures 6, 7, and 8 demonstrate the deformed mesh of PLAXIS footing models, as well as the distribution of vertical displacement in the case study. The results obtained are detailed as shown below:

4.1 Effect of shear strength parameters
Two shapes of footing are considered in this study, square footing and rectangular footing.

4.1.1 Square footing
The results from soil 1, their properties mentioned Table 1 for the square footing which is illustrated by Figure 9 that shows the difference in conformity of the soft soil model with the results of the experimental according to the value of the shear strength parameters, there was a match between the finite element analysis curve and the practical load – settlement curve at the initial stage, while it was underestimation at the latest state of loading.
Figure 6. The mesh and geometry model for soil 1 (C=70).

Figure 7. The mesh and geometry model for soil 2 (C=25)
**Figure 8.** The model's vertical settlement under foundation loading distributed at the middle.

**Figure 9.** The result of verification between numerical and experimental for clay soil C/70

### 4.1.2 Rectangular Footing
Figures 10 and 11 explain the results were obtained from soil 2 and 3 for the rectangular footing using soft soil clay, their properties are mentioned in Table 1. Whereas clay soil for shear strength parameters ($c=16$) gave the closest match to the experimental load – settlement behavior.
4.2 Effect of internal friction angle

The influence of the internal angle of friction on bearing capacity is seen in Figure 12 for simulation of the case study of soil 1, its shear strength parameters (\( c = 70 \)), then it was observed that when the internal friction angle increased the bearing capacity increased, as the angle of internal friction increases, so the clay's shear strength increased, and thus increase the bearing capacity and matching between the numerical and experimental that indicate a good agreement.
Figure 1. The effect of internal friction angle on bearing capacity for Soft Soil model for soil 1.

4.3 Effect of footing size

Three cases are selected in a square shape with widths of 0.8 m, 5 m, and 10 m. For the three models, Figure 13 depicts the results of the representation of normalized pressure versus settlement over foundation width (S/B). As the foundation width increased by (10%) , the bearing capacity rises as well, as indicated in Table I at various rates. There was a 79 percent increase in bearing capacity at a proportion of increasing raft width of (6.25), so that in the state that foundation width increased by (12.5), the average equals (144 percent). The reason for this is that the angle of friction is present in the inputs used to represent this situation, resulting in a modest increase in bearing capacity by raising the foundation width.

Table 2. Increase in bearing capacity as raft width increases for soil 1.

| Models Types             | Results of raft width (5m) | Results of raft width (10 m) |
|--------------------------|----------------------------|-----------------------------|
|                          | Increased of bearing capacity with respect to raft width (8 cm) (%) | Ratio of footing width $\frac{B(5m)}{B(0.8)}$ | Increased of bearing capacity with respect to raft width (8 cm) (%) | Ratio of footing width $\frac{B(10m)}{B(0.8)}$ |
| Soft Soil Model          | 79                         | 6.25                        | 144                         | 12.5                        |
5. Conclusion

In this study, numerical evaluation using PLAXIS-3D (V.20) was performed to simulate the behavior of clay soil by soft soil model. It was concluded that: The soft soil model presents good agreement with experimental results when the value of shear strength is low for rectangular footing. The soft soil model represented and simulate the behavior of soft soil. The soft soil model gives underestimation results at the latest state of loading when the shear strength is a high value (stiff clay) for the square footing. An increase in the foundation width led to an increase in bearing capacity, however, bearing capacity increased by around (79 %) for an increase in footing width of (6.25), so it was about (144%) for (12.5). The increasing of internal friction angle led to an increase in bearing capacity and show a higher match between experimental and theoretical load - settlement curve.

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