Numerical Simulation of Shallow Foundation Behavior Rested on Sandy Soil

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Abstract. The scope out of this paper, is a numerical evaluation of the behavior of shallow foundation rested on sandy soil exposed to axial load using “PLAXIS 3D 2020 software”. Different types of models are used for the simulation of foundation behavior that are Mohr-Coulomb model (MC), Hardening soil model (HS), and Hardening soil model with small-strain stiffness (HSS). The effect of three parameters (footing shape, soil saturation and footing size) are studied on three types of sandy soil having different internal friction angles. It can be observed from the result that Mohr-Coulomb model are identical with the curve at the elastic zone and overestimated at the plastic zone. The results are more realistic when using the constitutive hyperbolic hardening soil model compared with Mohr-Coulomb model. Better and closer to the practical result were observed when using HSS model. After the application of (HSS), it was concluded that is more realistic and gives greater value to estimate the behavior of small-scale shallow foundation in sandy soil compared to Mohr-Coulomb models and hardening soil model. Foundation bearing capacity for dry sandy soil is greater than for saturation one, with a percentage of increase equal 12.5, 30, and 27% for MC, HS, and HSS models respectively.

Keywords: Finite element; sandy soil; shallow foundation; PLAXIS.

1. Introduction

A foundation is the portion of a structure that transmits the load pressure of the structure to the ground. While planning to design a footing, it is necessary to know the type of soil, it behaves and the bearing capacity. When designing the foundation, the applied load should be less than the allowable capacity of the foundation. In order to model the stress and strain behavior of the soil, various constitutive models have been developed and apply into numerical models to use in geotechnical engineering application, in addition to investigating and analyzing structural problems of soil for different loading conditions [1]. The objective of the study to compare the results of PLAXIS 3D program that was used in this paper and the experimental load–settlement curve and find the best and closest match to the practical results. This topic has been studied by several researchers, and in this section a number of them are reviewed: Moayed et al. [2] used FLAC3D analysis of plate load test results in the case of loose and dense sandy soil was used to investigate the effects of chamber dimension on plate load test results are investigated. The experiments conducted on 30×30 cm plate load tests with 1×1×1 m chamber show that the boundary conditions have no significant effect on the results and thus they are applicable to in situ conditions.

Muntau and Bathaeian [3] used a well-documented experiment of shallow penetration into sand for the validation of the soft particle code (SPARC). For these simulations a hypoplastic material model for sand with calibration for the model sand is implemented in SPARC. Results show that SPARC performs better at predicting the trajectories of particles under the foundation, which consequently leads to better...
estimation of the load-settlement behavior [3]. Thakur and Dutta [4] conducted experimental and numerical analysis assessing the bearing capacity on three sands (S1, S2, S3) on square footings at a relative density of 30%. Results revealed that numerically recorded bearing capacity was slightly higher compared to the one recorded experimentally for all footings on sands (S1, S2, S3). Further, the experimental results validated the results acquired numerically with an average deviation of 3.25% [4].

2. Finite element analysis and mesh generation

PLAXIS 3D 2020 software was used for explaining and analyzing the soil behavior and its settlement subjected to vertical loading conditions, to achieve that three constitutive models used in this study that are Mohr Coulomb model (MC), Hardening soil model (HS) and Hardening soil model with small strain stiffness mode (HSs).

In the finite element approach, the stress-strain correlation of a practical material is represented by constitutive models that represent the behavior of the soil in a single element. The soil behavior simulates by the constitutive models, which is the main purpose with sufficient validity under all loading conditions [1].

On the basis of the mechanical law (Hooks law of linear elasticity and Coulomb’s law of perfect plasticity) easy and compound models were defined [5,6]. Finite element analysis was conducted using “PLAXIS 3D 2020” software”. In the finite element approach, the material is separated into a number of elements. All the element contains a number of nodes. All nodes have a number of degrees of freedom agreement to individual value of the undetermined in the problem of boundary value to solve for this purpose subdivide geometry into element compassion the finite element mesh [5,6].

Generate mesh should be adequately fine to get an exact numerical conclusion. On another side, very fine mesh should be ignored since this will lead to intemperate extreme calculation. This study used medium mesh for soil and footing after that refine mesh utilizes for plate footing. The basic soil element of “PLAXIS 3D 2020” finite element mesh described by the 10-Node tetrahedral elements were used to model and represent the soil and 6-Node plate use to simulate the behavior of footing as shown in Figure 1 [7].

3. Material properties of the studied soil

In this study, properties of the soil are based on Thakur and Dutta work [4]. Three types of sandy soil are used, designated as (S1-S2-S3), and its properties are shown in Table 1 moreover, the consolidated drained triaxial test (76 mm height and 38 mm in diameter) was conducted, to determine the shear strength parameters and test setup includes a test tank (700×450×600 mm). The footing is constructed of iron plate 10 mm thick and the dimensions are (80×80 mm). The properties of footing material are shown in Table 1.
Table 1. Properties of the studied soil [4].

| Material       | S1  | S1  | S1  | S2  | S2  | S2  | S3  | S3  | S3  | Footing |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|---------|
| Model name     | MC  | HS  | HSS | MC  | HS  | HSS | MC  | HS  | HSS | LE      |
| Type of drainage| D   | D   | D   | D   | D   | D   | D   | D   | D   | NP      |
| \( \gamma_{\text{dry}} \) (kN/m\(^3\)) | 14.38 | 14.38 | 14.38 | 14.89 | 14.89 | 15.15 | 15.15 | 15.15 | 78.5  |
| \( \gamma_{\text{sat}} \) (kN/m\(^3\)) | 18.83 | 18.83 | 19.12 | 19.12 | 19.29 | 19.29 | 19.29 | 19.29 | -     |
| Cohesion, \( c' \) (kPa)       | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | -       |
| \( \phi^0 \)      | 33.37 | 33.37 | 33.37 | 36.52 | 36.52 | 39.47 | 39.47 | 39.47 | -     |
| \( E' \) (kPa)     | 4800 | 4800 | 4800 | 5200 | 5200 | 5500 | 5500 | 5500 | 210\times10^6 |
| \( \nu^0 \)       | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.3  | 0.2  |
| \( \psi \) (\( \phi^0 \)-30) | 3.37 | 3.37 | 3.37 | 6.517 | 6.517 | 9.47 | 9.47 | 9.47 | -     |
| \( E_{50}^{ref} \times10^3 \) | -   | 22.6 | 22.6 | -   | 24.5 | 24.5 | -   | 25.91 | 25.91 |
| \( E_{agg}^{ref} \times10^3 \) | -   | 11   | 11   | -   | 11.4 | 11.4 | -   | 11.61 | 11.61 |
| \( E_{ur}^{ref} \times10^3 \) | -   | 67.85 | 67.85 | -   | 74.5 | 73.5 | -   | 77.74 | 77.74 |
| Exponential Power \( m^* \) | -   | 0.5  | 0.5  | -   | 0.5  | -   | -   | 0.5  | -     |
| Initial shear modulus \( G_0^{ref} \times10^3 \) | -   | 100  | -   | -   | 55.66 | -   | -   | 70.97 | -     |
| Shear strain \( \gamma_{ur} \times10^3 \) | -   | 0.1993 | -   | -   | 0.2181 | -   | -   | 0.2357 | -     |
| \( P_{\text{ur}} \) | -   | 100  | -   | -   | 100   | -   | -   | -    | 100   |
| \( R_{\text{ur}} \) | -   | 1    | -   | -   | 1     | -   | -   | -    | 1     |
| \( R_{\text{ref}} \) | -   | 0.9  | -   | -   | 0.9   | -   | -   | -    | 0.9   |

LE: Linear Elastic; D: Drained; NP: Non-porous; *: Estimated based on correlations [9].

4. Results and discussion
In this section, it will review the result obtained from the analysis conducted after studying some of the parameters that affect the foundation behavior.

4.1 Effect of the constitutive model used.
For the purpose of studying the simulation using different models, the analysis of the pressure-settlement curve is done using the inputs previously mentioned in Tables 1. Figures 2 and 3 show the geometry of footing models by “PLAXIS 3D 2020” and the distribution of vertical displacement of the case study. The comparison between numerical and experimental load-settlement curves appears in Figures 4, 5, and 6. The result of the Mohr-Coulomb model appears to be matching in the elastic zone, then, it is overestimated and deluding at the last level of loading because it behaves linear elastic perfectly-plastic. It was observed that the simulation by the Hardening soil model gives good results compared to Mohr-Coulomb because the Hardening model elastoplastic and it behave closest to soil behavior.
Figure 2. Geometry of foundation model.

Figure 3. Distribution of vertical settlement under loading of foundation at the center of the models.

Figure 4. Load–settlement response of various soil model for S1.
4.2 Effect of footing shape

The impact of the shape of footing on the foundation bearing capacity was examined by performing numerical analysis of three models, 10 mm thick iron plate that is a square shape of width 80 mm, rectangular with 65×98 mm and circular with a diameter 90 mm footing plate] test and assume the same properties of soil, see Table 1. The test evaluation appears that the bearing capacity of sandy soil for 80 mm square plate model is more prominent than that for the 65×98 mm rectangular model. The comparison of bearing capacity gotten for these three diverse shape footings has appeared in Figure 7. From this figure, it is obvious that the bearing capacity for 80 mm square plate is generally greater than those gotten for 65×98 mm rectangular by about 7.4% just in the Mohr-Coulomb model and 90 mm diameter for the circular plate. The same result was found as per Patel and Bhoi [20]. Effect of different shape of footing on its load settlement behavior (circular, square, and rectangular according to square and circle footing shape result but disagreement with rectangle result [10]. Figures 8 and 9 show that the results are nearly identical in three different shapes of footing for Hardening and Hardening with a small strain stiffness model.
Figure 7. Bearing capacity for different footing shape using MC model.

Figure 8. Bearing capacity for different footing shape using HS model.

Figure 9. Bearing capacity for different footing shape using HSS model.
4.3 Effect of soil saturation
The effect of soil saturation on the bearing capacity of foundation conducted on the sandy soil type (S1) using the three models appears in Figures 10, 11, and 12. The results of the analysis for saturation soil using the same properties appeared in Table 1 except the soil assume to be saturation. A comparison between dry and saturated soil show that the bearing capacity for dry soil greater than saturation soil because the effective stress in dry soil greater than in saturated soil [11,12]. The bearing capacity of foundation in dry soil increased by 12.5%, 30%, and 27% by using Mohr- Coulomb model, hardening soil model, hardening soil with small strain model respectively.

![Figure 10. The effect of saturation on bearing capacity using MC model.](image1)

![Figure 11. The effect of saturation on bearing capacity using MC model.](image2)
4.4 Effect of footing size

Three cases were represented in a square shape of 8 cm, 1 m, as well as a width of 10 m. The results of the representation of idealization settlement over the footing width (S/B) verse pressure the three models are shown in the Figures 13, 14, 15, and 16. It can be observed that there was an increase in bearing capacity at 10% footing width, when increasing the width of the foundation, with different percentages shown in Table 2. It can be seen that at ratio of increasing in raft width of 12.5 there was an increase of bearing capacity about 278% so that in case increasing raft width of 125 the average equals 1078% because when the width of the foundation increases in sandy soil, the depth of the stress-affected soil increases under the foundation and the bearing capacity increases.

| Models types | Results of raft width (1 m) | Results of raft width (10 m) |
|--------------|-----------------------------|-------------------------------|
|              | % Increase of bearing capacity | Ratio of footing width | % Increase of bearing capacity | Ratio of footing width |
| MC           | 233.3                       | 12.5                         | 1380                        | 125                        |
| HS           | 200                         | 12.5                         | 854.6                       | 125                        |
| HSS          | 250                         | 12.5                         | 1000                        | 125                        |
| Average      | 277.7                       | 12.5                         | 1078.2                      | 125                        |

Figure 12. The effect of saturation on bearing capacity using HSS model.

Figure 13. The effect of the shape of foundation on bearing capacity using MC model.
Figure 14. The effect of the shape of foundation on bearing capacity using HS model.

Figure 15. The effect of the shape of foundation on bearing capacity using HSS model.

Figure 16. Footing width–bearing capacity relationship for various model.
5. Conclusions
In this work, a numerical exploratory was performed to analyze the load–settlement relation of square footing exposed to vertical load using “PLAXIS 3D 2020”. It can be concluded the following based on the result of the current study:

- Comparison of the numerical analysis using MC, HS, and HSS models of footing rested on sand, with the practical results show that Mohr’s gives a higher result.
- The result obtained from MC model matches the curve at the elastic zone after that in the plastic zone be over predict, hence, this model is not recommended for use especially in the final stages of loading.
- The simulation using the constitutive hyperbolic HS model is more realistic and gives greater value to estimate the behavior of small-scale shallow foundation in sandy soil compared to MC model, but the best and close to the practical result were observed in the HSS model.
- Foundation bearing capacity for dry sandy soil is greater than for saturation one, with a percentage of increase equal 12.5, 30, and 27% for MC, HS, and HSS models respectively.
- The bearing capacity increased when the footing width increased. It can be seen that at ratio of increasing in raft width of 12.5, there was an increase of bearing capacity about 278% so that in case increasing raft width of 125, the average equals 1078.

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