Influence of Loading and Soil Modeling Approach on Soil-Shallow Foundation Interaction

Sujay Teli, Palak Kundhani, Virag Choksi, Pritam Sinha, and Kannan K. R. Iyer

Abstract Soil-foundation interaction studies are quite useful to evaluate the behavior of shallow foundations, especially for flexible foundations. The soil and foundation parameters which affect the base pressure and settlement below shallow foundations includes the type of soil, soil compressibility, modulus of elasticity of soil, foundation dimensions, and thickness. Additionally, variation in loading parameters also have significant effect on the behavior of foundation. The foundation may behave as flexible or rigid foundation depending on the variation in loading. Hence, it would be interesting to understand the influence of variation in loading on behavior of shallow foundations. In this regard, the present study evaluates the effect of change in magnitude of loading on shallow foundations. For the study isolated foundation and raft foundation have been considered and analysed in Staad Pro. Four different magnitude of loading on the columns supported by the foundation have been considered in the study. Further, the foundations have been modeled in PLAXIS 2D software and the results have been compared with that obtained from STAAD Pro. in order to understand the influence of modeling soil as discrete springs (in STAAD Pro.) and continuum (in Plaxis 2D). From the study, it is observed that magnitude of loading has significant influence on behavior of foundation. The base pressure and settlement

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obtained from STAAD Pro. analysis is relatively uniform. However, the base pressure distribution obtained from PLAXIS 2D analysis varies significantly, although the settlement response is more uniform. The study demonstrates the soil-foundation interaction response of shallow foundations under different loading condition by using STAAD Pro. and Plaxis 2D analysis.

Keywords Loading · Shallow foundation · Soil-foundation interaction · Base pressure · Settlement

1 Introduction

For analysis and design of any geotechnical system that includes various foundations, retaining walls, tunnels, etc., which are below the ground level; one needs to analyze the soil using its properties obtained from the geotechnical investigation. To model the soil there are various softwares available. It is generally assumed that the contact pressure distribution is uniform beneath the flexible foundation but considering the uniform distribution of contact pressure is unreasonable and its proper distribution pattern should be considered [1]. The model should be chosen so as to provide a realistic answer to the particular problem [2]. The use of modeling methods sometimes depend upon the software. Soil condition same as field conditions cannot be modeled in any software, however a nearly similar condition can be generated with certain assumptions. Defining sub-surface soil condition is mandatory because different rigid and flexible foundations having same Young's modulus of foundation material yield different results in varying subsurface conditions [3].

Plaxis 2D is a commonly utilized software to model the foundation-soil interaction. Plaxis allows different types of soil modeling but Mohr-Coulomb model is the simplest model and widely use due to its simplicity. In the Mohr-Coulomb model soil is modeled as continuum, in which soil is considered as linear elastic perfectly plastic [4] (Fig. 1). In comparison, the typical stress-strain for linearly elastic material is depicted in Fig. 2, which explains the difference in considered soil response at higher strain values.

This model depends on the failure criteria given by the Christian Otto Mohr [5] that describes that the failure in material is due to the critical combination of normal stress and shear stress and the failure shear stress is the function of the normal stress and can be given as,

$$\tau = f(\sigma) \tag{1}$$

where

τ = Shear stress at failure plane,
σ = Normal stress at failure plane.

This function gives curvilinear failure envelope. As per Charles Augustin de Coulomb [5] we can restrict the behavior of the failure envelope of soil to a straight

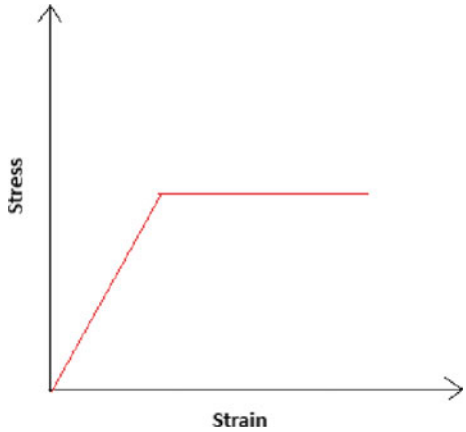

Fig. 1 Typical Stress-strain relationship of elastic perfectly plastic material

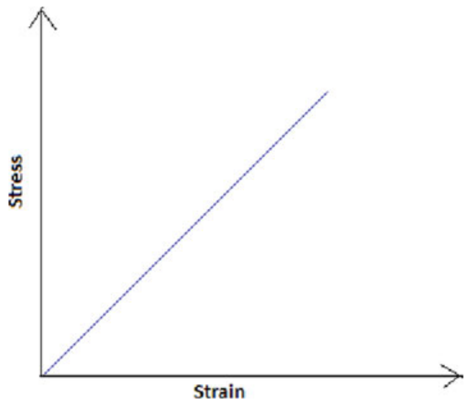

Fig. 2 Typical Stress-strain relationship for linear elastic material

line and the failure envelope for $c - \phi$ soil can be given as

$$\tau_f = c + \sigma \tan\phi \tag{2}$$

where,

τ_f = Shear strength of the soil or shear stress on failure plane,
c = Cohesion of soil,
σ = Normal stress on failure plane,
ϕ = Friction angle of soil

The above relationship for failure envelope is known as the Mohr-Coulomb failure criterion

Using STAAD Pro., soil can be modeled using the Winkler's approach which is linear elastic approach in which the soil is represented by the number of closely spaced discrete linear elastic springs. Modulus of these springs is considered as modulus of subgrade reaction or subgrade modulus which is denoted as K_s. Modulus of subgrade reaction is defined as the pressure required to cause unit settlement of soil under loading.

$$\sigma' = K_s\delta \tag{3}$$

where, σ' = Pressure intensity

K_s = Modulus of subgrade reaction
δ = Settlement

Factors influencing the value of modulus of subgrade reaction are rigidity of foundation, the type of soil and intensity and location of loading. Modulus of subgrade reaction (K_s) can influence the design parameters of foundation. Increase in K_s increases the value of base pressure beneath foundation and decrease the settlement values [6]. Results obtained from each method may vary as the approaches are different in the various methods. Mohr-Coulomb model (continuum approach) and Winkler's approach (discrete approach) are commonly used methods to model the soil. To understand which approach is suitable for a given condition, the comparison of the results of these two approaches would be helpful. This study attempts to compare the result of two methods of soil modeling (Winkler's approach and Continuum approach using Mohr-Coulomb model) using STAAD Pro. and PLAXIS 2D softwares, respectively; for two types of foundations (Isolated foundation and Raft foundation), two thickness of the foundation (0.5 m and 0.9 m) and different magnitude of loading. Lacustrine clay is considered for the study.

2 Methodology

2.1 PLAXIS 2D Model Generation

For PLAXIS 2D analysis, type of foundation, load intensity, foundation thickness are the variables considered for the study. Isolated foundation of 2 m × 2 m and Raft foundation of 7 m × 7 m are considered for the study. Column is considered at the center of isolated foundation and four columns are considered at the four corners of raft with 1 m offset. Two thickness of 0.5 and 0.9 m were taken as a part of study to vary the rigidity of foundation. The loading is applied as point load with values varying as 100, 300, 600 and 1000 kN load. Lacustrine clay is considered for the study [7] and the properties of clay are listed below. The variables considered in the study are listed in Table 2. Figure 3 depicts typical model generation in Plaxis 2D (soil properties as per Table 1).

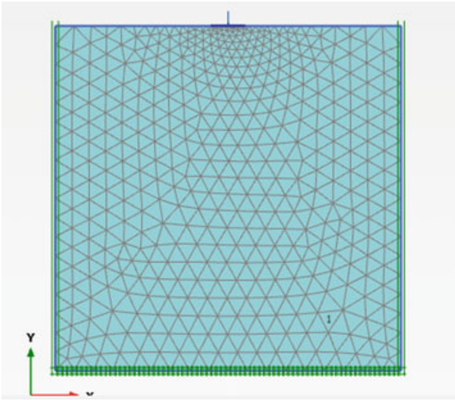

Fig. 3 Model generation in Plaxis-2D

Table 1 Soil properties used in STAAD Pro. and PLAXIS 2D analysis

Properties	Lacustrine clay
Dry unit weight (Υ_d) (kN/m^3)	17
Saturated unit weight (Υ_{sat}) (kN/m^3)	18
Modulus of elasticity (E) (kN/m^2)	10,000
Poisson's ratio (u)	0.3
Cohesion (c) (kN/m^2)	10
Friction angle (ϕ)	30
Drainage condition	Drained

Table 2 Variables considered in the study

Parameter	Variables
Foundation type	Isolated foundation and Raft foundation
Foundation thickness	0.5 and 0.9 m
Load values (total load for isolated foundation and load for one column for raft foundation)	100, 300, 600, 1000 kN

2.2 STAAD Pro. Model Generation

In STAAD Pro. using Winkler's approach all the models of isolated foundations and raft foundations were generated. As STAAD Pro. does not have any specification table for soil properties, the only variable for soil is modulus of subgrade reaction, K_s [8]. In this study, for comparison of STAAD Pro. and PLAXIS 2D results, the ratio of average base pressure and average settlement obtained from PLAXIS 2D analysis is used to compute the value of K_s (refer Eq. 4) and the same has been applied in corresponding STAAD Pro. model as soil stiffness. Figure 4 shows typical isolated foundation with point load and soil spring supports defined in STAAD Pro.

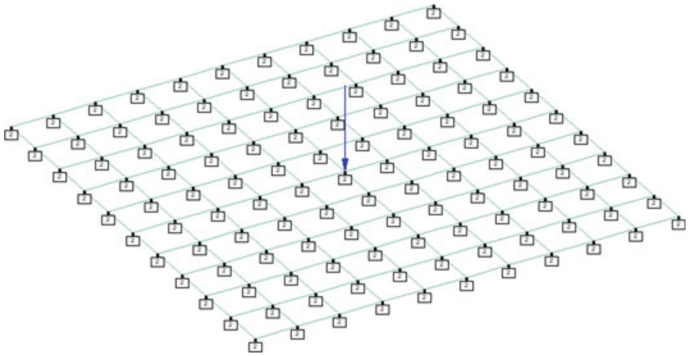

Fig. 4 Typical isolated foundation with point load in STAAD Pro.

$$\text{Modulus of subgrade reaction} = \frac{\text{Average base pressure beneath the foundation}}{\text{Average settlement beneath the foundation}} \tag{4}$$

3 Results and Discussion

3.1 Comparison of Results from STAAD Pro. and PLAXIS 2D Analysis

The result output for the maximum, minimum and average values of base pressure and settlement values obtained from PLAXIS 2D and STAAD Pro. analysis for each case is compared and the results are presented in Tables 3, 4, 5 and 6. Figure 5 depicts

Table 3 Base pressure values below raft foundation

Load value (kN)	Raft thickness (m)	STAAD Pro. result (kN/m^2)			Plaxis 2D results (kN/m^2)		
		Max.	Min.	Avg.	Max.	Min.	Avg.
100	0.5	20	20	20	76	14	25
100	0.9	29	29	29	111	20	36
300	0.5	37	36	36	130	25	44
300	0.9	46	46	46	156	32	55
600	0.5	63	59	61	183	43	70
600	0.9	71	70	70	197	51	80
1000	0.5	97	91	94	223	69	101
1000	0.9	103	102	103	232	77	110

Table 4 Base pressure values below isolated foundation

Load value (kN)	Raft thickness (m)	STAAD Pro. result (kN/m^2)			Plaxis 2D results (kN/m^2)		
		Max.	Min.	Avg.	Max.	Min.	Avg.
100	0.5	37	37	37	123	25	44
100	0.9	46	46	46	147	32	55
300	0.5	87	87	87	181	65	92
300	0.9	96	96	96	179	74	100
600	0.5	162	162	162	201	56	156
600	0.9	171	171	171	211	56	166
1000	0.5	262	262	262	322	56	258
1000	0.9	271	271	271	327	61	268

Table 5 Settlements values below raft

Load value (kN)	Raft thickness (m)	STAAD Pro. results (mm)			Plaxis 2D results (mm)		
		Max	Min	Avg	Max	Min	Avg
100	0.5	20.8	21.0	20.6	26	26	26
100	0.9	30.9	31.0	30.9	37	37	37
300	0.5	37.3	39.3	38.1	46	46	46
300	0.9	48.8	49.1	48.9	59	59	59
600	0.5	65.6	69.5	67.1	77	77	77
600	0.9	78.9	79.6	79.2	89	89	89
1000	0.5	108.8	115.5	111.5	121	121	121
1000	0.9	121.4	122.6	121.9	134	134	134

Table 6 Settlements values below isolated foundation

Load value (kN)	Raft thickness (m)	STAAD Pro. result (mm)			Plaxis 2D results (mm)		
		Max.	Min.	Avg.	Max.	Min.	Avg.
100	0.5	11.1	11.1	11.1	13	13	13
100	0.9	14.2	14.2	14.2	17	17	17
300	0.5	30.8	30.8	30.8	33	33	33
300	0.9	35.5	35.5	35.5	37	37	37
600	0.5	80.9	80.9	80.9	78	78	78
600	0.9	87.6	87.6	87.6	84	84	84
1000	0.5	166.9	166.9	166.9	166	147	156
1000	0.9	179.5	179.5	179.5	179	157	168

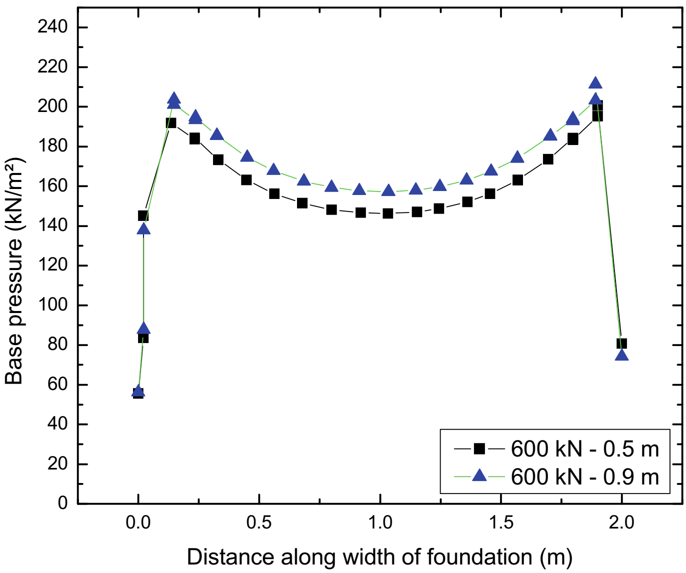

Fig. 5 Base pressure distribution for isolated footing with 600 kN loading on lacustrine clay from PLAXIS 2D analysis

typical base pressure distribution for isolated foundation on lacustrine clay subjected to 600 kN point load as obtained from PLAXIS 2D analysis. Figure 6 depicts the typical settlement variation along width of isolated foundation for the same case from PLAXIS 2D analysis.

From the Tables 3, 4, 5 and 6, it is noted that the average values of the base pressure beneath the foundation obtained by both the approaches (Winkler's approach and continuum) are comparable. The average values of settlement obtained by the Winkler's approach (using STAAD Pro.) are slightly lower for raft foundation than that obtained from PLAXIS 2D. For isolated foundation, the settlement values obtained from STAAD Pro. are lower as compared to that obtained from PLAXIS 2D analysis for 100 kN and 300 kN loading. However, for 600 kN and 1000 kN loading, the settlement values obtained from STAAD Pro. analysis are slightly higher for the isolated foundation as compared to results from PLAXIS 2D.

It may be noted that STAAD Pro. analysis is 3-dimensional analysis while PLAXIS 2D analysis is 2-dimensional analysis. Hence in STAAD analysis, the stress in vertical direction due to loading is distributed in 3-dimensions including both the lateral directions, whereas in PLAXIS 2D analysis, the vertical stress is distributed in vertical and one lateral direction only. Further, the observation for lower settlement for 600 and 1000 kN for isolated foundation analyzed in PLAXIS 2D as compared to STAAD Pro. analysis can be due to initiation of shear failure. However, this aspect needs further study to conclude.

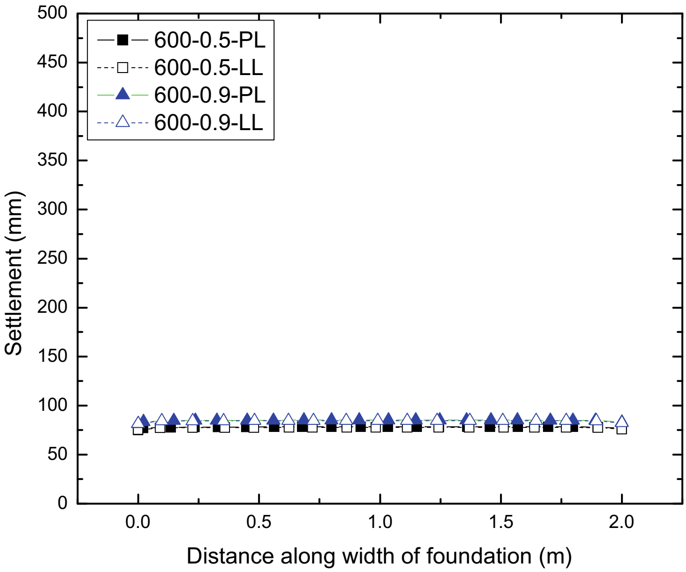

Fig. 6 Settlement distribution for isolated footing with 600 kN loading on lacustrine clay from PLAXIS 2D analysis

Further, the settlement values increase as the thickness of the foundation increases. Increase in load value increases the total settlement. Increase in thickness of the foundation and loading increases the value of base pressure.

4 Conclusions

1. Increase in load values increases the base pressure and settlement values for both isolated and raft foundation in lacustrine clay.
2. Increase in the thickness of isolated foundation and raft increases the value of maximum base pressure and settlement.
3. Average values of base pressure are comparable for the Winkler's approach (in STAAD Pro.) and Continuum soil modeling approach (in PLAXIS 2D) with maximum variation of about 25%.
4. Average values of settlement obtained are, in general, lower based on Winkler's approach for raft foundation as compared to continuum approach. Settlement values for 100 and 300 kN loading for isolated foundation is observed to be lower with Winkler's approach as compared to continuum approach. However, for higher loading, Winkler's approach yields higher settlement as compared to continuum approach.
5. Winkler's approach for modeling soil in STAAD Pro. yields more uniform pressure and settlement distribution below the foundation and raft.

6. The effect of variation of modulus of subgrade reaction at different location below foundation can be considered in future studies for more realistic understanding of soil-structure interaction.

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