Numerical Study on Response of Laterally Loaded Piles in Soils

Amit Jain¹ & A.K. Sahu²

¹Civil Engineering Department, Delhi Technological University
²Professor, Department of Civil Engineering, Delhi Technological University, Delhi

Abstract: Parametric studies are done to examine the influence of soil layering, pile slenderness ratio and cross-sectional shape on the response of piles of laterally loaded in homogeneous and heterogeneous soil in which the soil shear modulus varies discretely with depth. Numerical method such as finite element method is used for presenting the analysis of laterally loaded piles with circular and rectangular cross section. The analysis is developed by solving the displacement of the pile-soil system derived. The Abaqus software is used for estimating the pile-head deflection and development of stresses which is mainly used in design purposes. The result shows that the soil layering with different soil shear modulus influences the lateral response of pile. The lateral response in the homogeneous soil system is affected by the cross-sectional shape of the pile. The lateral responses of piles in soil layered systems were mostly affected by the stiffness and thickness of the top soil layer. The pile head deflection varies in the cases in which the pile slenderness ratio was less than twenty-five in different layered soil system. Using this analysis, deflection in pile, stress profiles and curve of the lateral displacement and the stress variation in the pile can be obtained quickly along the entire pile length. Also, the stresses developed in the surrounding soil of the pile were analyzed. Various numerical examples based on this analysis are provided.

Keywords: Circular pile; Rectangular pile; Lateral Load; Continuum-based mechanism; Heterogeneous soil; Numerical Solution; Abaqus Software.

1. Introduction

Some ground surfaces have weak or poor soil conditions as soil may be composed of clay, loose saturated sand on the construction site. So it may be necessary to transmit the building loads to deeper more stable soil and for that purpose we mainly use piles. Piles are widely used to transfer vertical and lateral loads to the ground. In many structures like in tall buildings, bridges, dams, offshore platforms the major problem arises due to the lateral load as wind gust, seismic activity, wave action, etc. For solving this problem, laterally loaded piles in homogeneous or heterogeneous soils in which the properties of soils vary with depth are analyzed either by using the p-y method, which is mainly based on the beam-on-foundation concept or by using continuum-based numerical methods, such as finite element method, finite-difference method and the boundary element method. Reese and Matlock (1956) worked on the laterally loaded piles in heterogeneous soil and presented the non-dimensional curve which can be used to obtain deflections, moments, shear at any point along the length of the pile. Broms (1964) worked on lateral resistance of vertical piles and concluded that it can be used for short and long piles and for both cohesion and cohesion less soil but not applicable to layered soil and c-ço soils. Reese and Welch (1974) worked on dry and stiff clay and obtained p-y curves and bending moment curves. The p-y curves determine the relation between the lateral pile displacement y and the resistance p offered by the soil. The results are obtained easily and quickly because of the one-dimensional differential equation of pile that is solved with the nonlinear p-y curves taken as input. But the major drawback of this method is that they can’t provide accurate predictions and actual mechanism about their results because the 3D pile-soil interactions are different for different pile-soil conditions (Li Yan and P.M. Byrne 1992).

While, in continuum-based numerical mechanism, finite element method can provide accurate solutions for the 3D pile soil interaction. The solutions obtained from this approach are quick as variables required for the geometry and numerical mesh is less. In this paper, analytical approach is used for analyzing the soil interaction to determine the pile head deflection and stress variation in the pile and the soil. Here, main contributions for the analysis are the cross-sectional shape of the pile, study of responses of pile in heterogeneous soil with variation of soil modulus with depth. Numerical examples are provided for analyzing the problem of pile-soil model with the help of ABQUS 6.10 software.
2. Numerical Analysis

2.1 Pile-Soil Interaction

The behaviour of the pile supported structure mainly depends on the type of pile-soil interaction. The contact between the pile and the soil surface can be both normal and tangential. A relatively small sliding is present in between pile and soil in the tangential direction and no slippage is observed in the normal direction along the pile-soil surface. For analyzing the response of the pile in the homogeneous and heterogeneous soil, finite element method is used in which the soil is treated as continuum.

2.2 Finite Element Method

Finite Element method is a versatile method. It’s greatest advantage is that the analyst has complete freedom to analyze the structure to any degree of refinement by increasing the no of elements, number of nodes in an element etc. and test all possible configurations to arrive at the final solution. It can be ideally used in the cases involving the complicated geometrics, loadings and boundary conditions. The main concept in the FEM involves division of given structure into smaller elements for analysis called finite elements and these elements are interconnected at a discrete number of joints/nodes. For analysis purpose, we combine each and every finite element equations to obtain the solution of the whole structure in the form of simultaneous equations. The main advantage of FEM is the ability to accommodate different boundary and loading conditions, can model composite structure involving regions with different properties. Here, for analyzing the problem of pile-soil model, we are using ABAQUS 6.10 software. It is a simulation program that can solve the problem ranging from relatively simple linear analysis to the most challenging non-linear simulations.

2.3 Parametric Study

A parametric study is done to examine the effects of the stiffness of the layered soil, cross-sectional shape of the pile and the slenderness ratio on the pile response. For getting the response, the soil layer is to be consider as discrete with depth.

To perform the parametric study, normalized pile-head deflection caused by the lateral force $F_a$ defined as “$U$” for layered soil profiles with different value of soil shear modulus “$G$” is considered ($G_i$ for the $i_{th}$ soil layered medium). The dimension of the sides of the rectangular pile is taken as “$W$” that produces the same area as that of a circular pile ($W=2\ r_p$). The length of the pile is taken as $L_p$.

3. Finite Element Modelling

The references for the properties of the soil and the pile, which are used in the numerical problems, are taken from engineeredge.com, geotechdata.info, supercivilcd.com.

3.1 Analysis of different shape of piles

A finite element model of the pile-soil interaction was developed using the finite element software ABAQUS/CAE.

In this, an elastic model was adopted for modelling the pile with the modulus of elasticity 30GPa and Poisson ratio 0.15. Rectangular and circular pile is considered in this analysis. The cross sectional dimension of the rectangular pile is 0.36m x 0.36m. The circular pile has a cross sectional diameter of 0.4m (both the piles have the same cross-sectional area approximately). The length of both the piles is taken same as 15m.

A single layer soil profile is considered with length 14.85m, breadth 10m, modulus 60 MPa and Poisson ratio 0.4. The section taken for both the pile and soil is solid and homogeneous. The tangential movement between the two parts, surrounding soil and pile, is provided with a friction value of 0.36. The outer surface of the pile is chosen as the master surface (because of more stiffness) and the inner surface of the soil medium which has been in contact with the pile is considered to be the slave surface. A relatively small sliding is taken in between the contact of two surfaces.

A relatively fine mesh is used for the pile than that of soil. In this model, the pile and the soil are modelled using eight-nodded solid continuum elements (C3D8R) to explain the continuum nature of the soil. In the FE model, the bottom of the pile is fixed to imitate the embedment of the pile and the outer surface of the soil medium is fixed to simulate the confinement of the soil. The boundary conditions and the load are step dependent. The lateral load (30kN) is applied in (-) x direction at the cited point that defines the rigid body motion at the top of the pile to examine the effect of the lateral load on the induced stress developed along the length of the pile and the soil and lateral displacement of the pile. Figure shows the lateral displacement and stress developed along the length of the pile.
Fig. 1. Rectangular pile soil model

Fig. 2. Circular pile-soil model

Fig. 3. Deflection in Rectangular pile

Fig. 4. Deflection in Circular pile

Fig. 5. Stress developed in Rectangular soil

Fig. 6. Stress developed in Circular soil

Fig. 7. Deflection along depth in rectangular pile

Fig. 8. Deflection along depth in circular pile
The observation about the maximum pile deflection and the maximum stress developed are recorded for both, Rectangular and Circular pile.

Table 1. Response of Different Shape of the pile

<table>
<thead>
<tr>
<th>Pile Shape</th>
<th>Maximum pile deflection (in mm)</th>
<th>Maximum stress produced (in MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>1.055</td>
<td>2.090</td>
</tr>
<tr>
<td>Circular</td>
<td>1.734</td>
<td>3.756</td>
</tr>
</tbody>
</table>

In analysis, it is found that the different cross-sectional shapes of the pile, as here rectangular and circular pile, with same area have different responses when we applied lateral load (assume all other factors are same).

3.2 Analysis in two-layered soil

Here, the response of the circular pile in a two-layered soil profile is observed. In this, two cases have been taken in which the breadth and the Poisson ratio is taken same as 10m and 0.40, respectively. The different properties taken for the top and the bottom layer of the soil are mentioned in Table 2.

Table 2. Properties in two-layered soil system

<table>
<thead>
<tr>
<th>Case</th>
<th>Length of the soil ( (H_1) ) (in m)</th>
<th>Soil modulus ( (G_1) ) (in MPa)</th>
<th>Top ( (H_2) ) (in m)</th>
<th>Bottom ( (G_2) ) (in MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.5</td>
<td>30</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>10</td>
<td>30</td>
<td>70</td>
</tr>
</tbody>
</table>

The cross sectional diameter of the circular pile is 0.40m. Length of the pile is 15m. The young modulus of the pile is 30 GPa and Poisson ratio 0.15. The section taken for both the pile and soil is solid and homogeneous. The tangential movement between the two parts, surrounding soil and pile, is provided with the friction value of 0.36. In the direction which is normal to the surface, a hard contact behaviour (no separation) is taken. The outer surface of the pile is chosen as the master surface and the inner surface of the soil mass which is contact with the pile is considered to be the slave surface. Tangential movement between the two layers of the soil is provided with the friction value of 0.001 and in radial (normal) direction, a hard surface contact behavior is taken. A relatively fine mesh is used for the pile than that of soil. In this model, the pile and the soil were modelled using eight-noded solid continuum elements (C3D8R) to explain the continuum nature of the soil. In the FE model, the bottom of the pile was fixed to imitate the embedment of the pile and the outer surface of the soil medium was fixed to simulate the confinement of the soil. The lateral load (40kN) was applied in (-) \( x \) direction at the cited point defining the rigid body motion at the top of the pile to examine the effect of the lateral load on the induced stress developed along the length of the pile and the soil and lateral displacement of the pile. Figure shows the lateral displacement and stress developed along the length of the pile.
Fig. 12. Stress in pile-soil model in CASE 2

Fig. 13. Displacement in pile in CASE 1

Fig. 14. Displacement in pile in CASE 2

Fig. 15. Curve between Pile Deflection (m) vs Depth (m) in CASE 1

Fig. 16. Curve between Pile Deflection (m) vs Depth (m) in CASE 2

Fig. 17. Curve between Stress (Pa) vs Depth (m) in CASE 1

Fig. 18. Curve between Stress (Pa) vs Depth (m) in CASE 2
The observation for both the cases is mentioned in the Table 3.

Table 3. Observation of the output result

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum pile deflection (in mm)</th>
<th>Maximum stress developed in pile (in MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.368</td>
<td>2.958</td>
</tr>
<tr>
<td>2</td>
<td>10.15</td>
<td>3.597</td>
</tr>
</tbody>
</table>

After analyzing, the magnitude of the pile deflection and stress developed in Case 1 is less than that of Case 2.

The result shows that in the layered soil system, here two-layered soil system, the lateral behaviour of the pile is mainly affected by the stiffness (soil modulus) and thickness of the top soil layer. The normalized head deflection and the stress developed in the pile is dependent on the soil modulus of the top soil layer in the layered soil system.

3.3 Analysis in three-layered soil

For analyzing the lateral-load response of the pile in three-layered soil profiles, three different soil layering cases (Case 1-3) are considered. Each layer of the soil profiles have different young modulus such that the average shear modulus is the same for all the cases.

For Case 1, soil modulus increases with depth, whereas for Case 3, it decreases with depth. In Case 2, the intermediate layer has the least value of soil modulus. The thickness for all the three layers of the soil is taken equal. Some properties of the three-layered soil profile in all the cases are given in the Table 4.

Table 4. Properties in three-layered soil system

<table>
<thead>
<tr>
<th>Case</th>
<th>Length of the soil (in m)</th>
<th>Soil modulus (in MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top (H₁)</td>
<td>Mid (H₂)</td>
</tr>
<tr>
<td>1</td>
<td>4.95</td>
<td>4.95</td>
</tr>
<tr>
<td>2</td>
<td>4.95</td>
<td>4.95</td>
</tr>
<tr>
<td>3</td>
<td>4.95</td>
<td>4.95</td>
</tr>
</tbody>
</table>

The breadth and the Poisson ratio of the soil is taken as 10m and 0.25 for all the three layers of the soil. The cross-sectional diameter and the length of the circular pile is 0.6m and 15m, respectively. The properties used for the pile is that of concrete with Young modulus of 30 GPa and Poisson ratio 0.15. The section is taken for the pile and soil is solid and homogeneous. The analysis that is performed on the pile-soil model consists of an initial step and one general analysis step which is Static, General. The tangential friction coefficient between the surrounding soil and the circular pile is provided as 0.55 and hard contact behaviour is taken normally.

The interaction properties in different layers of soil is also provided with a friction value of 0.001 in tangential direction and hard contact in normal direction. The elements used for the meshing is of hexahedron shape and eight noded solid continuum (C3D8R) to explain the continuum nature of the soil. The circular pile and the soil medium is meshed by providing 10 elements to the selected edges. The lateral load of 30kN is applied in (-) x direction to the pile. The bottom of the pile and the outer surface of the soil are fixed with Encastre conditions. After giving the properties and conditions, the model is run in Abaqus. Following figures are obtained after analysis.

Fig.19. Deflection in pile in CASE 1

Fig.20. Deflection in pile in Case 2
Fig. 21. Deflection in pile in CASE 3

Fig. 22. Stress developed in pile

Fig. 23. Stress developed in soil in CASE 1

Fig. 24. Stress developed in soil in CASE 2

Fig. 25. Stress developed in soil in CASE 3

Fig. 26. Deflection along depth in CASE 1

Fig. 27. Deflection along depth in CASE 2

Fig. 28. Deflection along depth in CASE 3
The observations are taken into account in Table 5.

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum Pile Deflection (in mm)</th>
<th>Maximum Stress developed in pile (in MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.739</td>
<td>1.665</td>
</tr>
<tr>
<td>2</td>
<td>1.328</td>
<td>1.665</td>
</tr>
<tr>
<td>3</td>
<td>2.092</td>
<td>1.665</td>
</tr>
</tbody>
</table>

After observing the result, it is found that the normalized head deflection is minimum in Case 2. The maximum stress developed in all the three cases is same as 1.665 MPa.

In the above problem, in which the average soil shear modulus were same in all the cases, the head deflection was found to be minimum in which the soil modulus decreases with depth.

### 3.4 Analysis with varying Pile slenderness ratio

The response of long and short piles is different under lateral loads. Therefore, it is necessary to examine the effect of the slenderness ratio on the response of the laterally loaded piles. For analyzing different layered soil profiles with varying pile slenderness ratio, different cases are taken.

A four layered soil profile of 16m (H1=4m, H2= 4m, H3=4m, H4=4m) is considered with the shear modulus of the soil (G1=10 MPa, G2=15 MPa, G3=25 MPa, G4=40 MPa) is increasing with depth and the Poisson ratio of the soil is 0.25 for all the layers. The cross-sectional diameter of the circular pile is 0.6m and the applied lateral force in (-) x direction at the top of the pile is 30kN. The same above properties is used for the circular pile. The cross-sectional diameter of the circular pile is 0.6m. Length of the pile is different for different cases as mentioned in Table 6.

<table>
<thead>
<tr>
<th>Case</th>
<th>Length of the pile (L_p) (in m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.15</td>
</tr>
<tr>
<td>2</td>
<td>10.15</td>
</tr>
<tr>
<td>3</td>
<td>12.15</td>
</tr>
<tr>
<td>4</td>
<td>15.15</td>
</tr>
</tbody>
</table>

The section taken for the pile and the soil is solid and homogeneous. The elements used for the meshing is of hexahedron shape and eight noded solid continuum (C3D8R) to account for the continuum nature of the soil. The circular pile is meshed by providing 8 elements and different layers of the soil medium is meshed with 11, 10, 9, 8 elements to the selected edges, respectively. The model is run in Abaqus for analysis after completion. Figure shows the lateral displacement and stress developed along the length of the pile.
The observations of the result are taken into account in Table 7.

### Table 7. Observation of the output result

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum Pile Deflection (in mm)</th>
<th>Maximum Stress Developed in pile (in MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.50</td>
<td>1.281</td>
</tr>
<tr>
<td>2</td>
<td>10.49</td>
<td>0.8870</td>
</tr>
<tr>
<td>3</td>
<td>10.43</td>
<td>0.8840</td>
</tr>
<tr>
<td>4</td>
<td>10.41</td>
<td>0.8911</td>
</tr>
</tbody>
</table>

While analyzing the laterally loaded pile, it was observed that when the pile slenderness ratio was increased but less than twenty-five in layered soil system, the pile head deflection in the pile decreased.

### 4. Conclusions

In this report, an analysis is done to formulate the response of the load applied laterally on the circular and rectangular piles in the homogeneous and heterogeneous soil deposits. In heterogeneous soil deposits, soil shear modulus increases linearly with depth or discrete values of shear modulus is taken for distinctly different layers.

Through this analysis, deflection in pile, shear stress profiles, slope of the deflected and shear curve can be quickly obtained along the entire pile length. From this analysis, the stresses developed in the surrounding soil of the pile were also obtained. The input values required for the analysis are that of pile geometry, thickness of the soil layers and the elastic constant of the pile and soil.

Parametric studies were done to evaluate the effect of pile cross-sectional shape, pile slenderness ratio and soil heterogeneity and layering on the lateral loaded piles, namely lateral deflection and development of the stresses. The lateral response is affected by the
cross sectional shape of the pile. For piles in layered soil system, the thickness and stiffness of the top soil layer mainly affects the lateral behavior of the pile. Various graphical representations were obtained after the analysis of the respective problem.

5. Acknowledgements

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6. References


