Finite Element Analysis of Pile-Soil-Cap Interaction Under Lateral Load

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ABSTRACT

Pile foundations must be capable of resisting not only the loads coming from the superstructure, but also the large lateral forces due to earthquakes, wind, wave etc. The pile caps which are often massive and deeply buried would be expected to provide significant resistance under the lateral loads. Several parameters influence to quantify the cap resistance against the lateral loading. Neglecting cap resistance results in estimates of pile group deflections and bending moments under lateral load are double the actual values (Mokwa & Duncan 2001). The 2D finite element analysis with the help of the software PLAXIS 2D is performed to investigate the cap resistance against the lateral load varying the position of cap and length of pile. It is observed from this study that, the pile cap resists a good amount of lateral load and interestingly these resistance increases as increases of position of cap from ground level.

1. INTRODUCTION

The deep foundations consist of groups of piles coupled together by concrete pile caps. The pile caps, which are often massive and deeply buried, would be expected to provide significant resistance to lateral loads. However, practical procedures for computing the resistance of pile caps to lateral loads have not been developed and for this reason, cap resistance is usually ignored. Neglecting cap resistance results in estimates of pile group deflections and bending moments under load that may exceed the actual deflections and bending moments by 100% or more. Advances could be realized in the design of economical pile-supported foundations, and their behaviour more accurately predicted, if the cap resistance can be accurately assessed.

An understanding of soil-pile-cap interactions and the mechanics of load transfer is necessary to develop a method that can be used to compute displacements, shears, and moments in pile groups. Pile caps are constructed to provide a connection between a structure and multiple single piles and are often subjected to vertical and lateral loads as well as overturning moments. Resistance to these loadings is provided by pile-soil-pile interaction, base and side friction along the concrete-soil interface, the rotational restraint provided by the pile-to-pile cap connection, and passive earth resistance. Research involving model tests, centrifuge tests, and full-scale tests has been conducted to study the lateral resistance of pile groups. Mokwa & Duncan (1999) concluded that influence of pile cap under lateral load is significant. More detailed studies on pile caps have provided significant insight regarding the lateral resistance of pile caps. Full-scale testing by Kim et al. (1979) on three different 2×3 pile groups indicated that pile cap deflections were “nearly double” for the same lateral loads with the pile cap base friction component removed. Mokwa & Duncan (2001) performed several full-scale tests on three different 2×2 pile caps and found that the passive resistance depends on the strength and stiffness of the soil along with the depth of cap embedment. Passive resistance contributed up to 50% of the total lateral resistance. Recently, El-Garhy et al. (2009) presented the results of experimental study on model piles to show the effect of pile cap elevation below the ground surface and pile spacing on lateral resistance of single pile and pile groups driven in sand. They concluded that the lateral carrying capacity of single pile and pile groups increase as the pile cap depth below the ground surface increases and as the spacing between piles in the group increases.

2. FINITE ELEMENT: BACKGROUND OF MODEL

Finite element techniques can be used to analyze complicated Geotechnical problem like pile-soil-pile cap interaction under the lateral load. A two-dimensional finite element programme PLAXIS 2D (Version 8) has been used to model pile, soil and pile cap using the concept of plain
strain condition. Plane strain condition results in a two-dimensional finite element model with only two translational degrees of freedom per node. The 15-noded triangle provides a fourth order interpolation for displacements and the numerical integration involves twelve Gauss points.

The interface elements are placed around the pile to model the interaction between the pile and the soil. A proper modelling of the pile-soil interaction is important to include the material damping caused by the sliding of the soil along the pile during penetration and to allow for sufficient flexibility around the pile tip. In order to simulate the behaviour of the soil, a suitable soil model and the appropriate material parameters have to be assigned to the geometry. In the software, soil properties are collected in material data sets and the various data sets are stored in a material database. From the database, a data set can be appointed to one or more clusters. The creation of material data sets is generally done after the input of boundary conditions. The Mohr-Columb model for soil modelling under drained condition is considered to investigate the phenomenon.

The mesh generation in finite element analysis is not only a difficult task but also critically important to achieve a better and accurate results of the problem. Before the mesh is generated, all material data sets should have been defined and all clusters and structures must have an appropriate data set assigned to them. The mesh generation requires a general meshing parameter which represents the average element size, $l_e$.

Here, this parameter is calculated from the outer geometry dimensions $(x_{\text{max}}, x_{\text{min}}, y_{\text{max}}, y_{\text{min}})$ and a Global Coarseness setting as defined in the Mesh Sub Menu.

$$l_e = \sqrt{\frac{(x_{\text{max}} - x_{\text{min}})(y_{\text{max}} - y_{\text{min}})}{n_c}} \quad (1)$$

Distinction is made between five levels of global coarseness: very coarse, coarse, medium, fine and very fine with the help of following guidelines of the software.

The beauty of the software is that it allows for a fully automatic mesh generation procedure, in which the geometry is, divided into elements of the basic element type compatible structural elements, if applicable. The mesh generation takes full account of the position of points and lines in the geometry model, so that the exact position of layers, loads and structures is accounted for in the finite element mesh. Once the mesh has been generated, the finite element model is complete.

Once mesh generation is completed successfully for desired condition, the models have to assign the initial conditions. The three initial conditions are (1) the initial groundwater conditions- the pore pressure can be generated on the basis of phreatic levels by using geometry line, (2) the initial geometry configuration- it enables to deselect the geometry clusters that are not active in the initial situation, (3) the initial effective stress state -this initial stress in a soil body are influenced by the weight of the material and the history of its formation. This stress state is usually characterised by an initial vertical effective stress $\sigma_{\theta,0}$. The initial horizontal effective stress $\sigma_{h,0}$ is related to the initial vertical effective stress by the coefficient of lateral earth pressure $k_0 (\sigma'_{h,0} = k_0 \sigma'_{\theta,0})$. This may be generated by $k_0$ or by using gravity loading (by default $k_0 = 1 - \sin \theta$). In this current study, consider the soil layer is dry and so there is no need to enter groundwater conditions.

The calculations program is used to define and execute calculation phases. It can be used to select calculated phases for which output results are to be viewed. During the execution of a calculation a window appears which gives information about the progress of the actual calculation phase.

3. MODEL GENERATION

Soil and pile system is modelled in PLAXIS 2D (Version 8), which is a finite element code particularly for geotechnical analyses, is utilized. The model is generated for plain strain condition with 15 node elements. The minimum dimensions of the draw area have to be finalised such that the geometry model will fit the draw area. This is done by keeping $x = 50$ m and $y = 25$ m in xy plane.

The soil is modelled by the geometry lines. The plate elements are considered for modelling of pile and cap. The interaction between the soil and the pile is modelled at both sides by means of interfaces. The interfaces allow for the specification of a reduced pile friction compared to the friction in the soil. A single pile is modelled. A uniform finite element mesh is utilized in all of the analyses. The basic principles followed in the analyses are based on the approach proposed by Taiebat & Carter (2000, 2002), with some minor modifications. The parameter considered to study for soil and pile are tabulated in Table 1 and 2. Typical values for the static stress-strain Modulus ($E$) is considered according to Bowles (1982).

Table 1: Properties of Soil for Study

<table>
<thead>
<tr>
<th>Properties of Soil</th>
<th>Cap Level</th>
<th>Other Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{\text{sat}}$ (kN/m$^3$)</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>$\gamma_{\text{unsat}}$ (kN/m$^3$)</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>$k_s$ (m/day)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$k_f$ (m/day)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$E_{\text{ref}}$ (kN/m$^3$)</td>
<td>$10 \times 10^6$</td>
<td>$48 \times 10^6$</td>
</tr>
<tr>
<td>$D$</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$C_{\text{ref}}$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$30^\circ$</td>
<td>$35^\circ$</td>
</tr>
<tr>
<td>$\psi$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Table 2: Properties of Pile and Pile Cap for Study

<table>
<thead>
<tr>
<th>Properties of Pile and Cap</th>
<th>Pile</th>
<th>Pile Cap</th>
</tr>
</thead>
<tbody>
<tr>
<td>(EA) in kN/m(\times10^6)</td>
<td>(2 \times10^6)</td>
<td>(2 \times10^6)</td>
</tr>
<tr>
<td>(EI) in kNm(^2)/m</td>
<td>(1.5 \times10^4)</td>
<td>(1.35 \times10^5)</td>
</tr>
<tr>
<td>Thickness ((d)) in m</td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Weight kN/m/m</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

A two dimensional finite element analysis is performed to observe the pile cap resistance. The Analysis is performed for elasto-plastic condition. The different geometric as well as finite element model is prepared by varying the position of pile cap from the ground level and pile length \(P_L\). Three position of pile cap is considered for this study; these are Case 1:-the position of top of pile cap at ground level, Case 2:-the position of top of pile cap at a depth of 0.2m from ground level, and Case 3:-the position of top of pile cap at a depth of 0.5m from ground level. The two considered pile length are 10m and 15m. The geometric and finite element model of a single pile of 10 m long with top of pile cap at ground level is shown in Figure 1 and Figure 2 respectively.

The cap has significant lateral resistance and the amount of resistance increases as the depth of pile cap increases from ground level. The lateral cap resistance are 33.16 %, 34.08 % and 35.43 % for different cases i.e. Case-1 (position of top of pile cap at ground level), Case-2 (position of top of pile cap at a depth of 0.2m from ground level) and Case-3 (position of top of pile cap at a depth of 0.5m from ground level) respectively. The increase in the lateral resistance may be attributed to the increase of passive resistance in the front of pile cap and the increase of friction resistance on the top surface of the pile cap as the depth of pile cap below ground level increases.

Fig. 1: Geometric Model of a Single Pile (Case I, \(P_L=10m\))

Fig. 2: FE Model of a Single Pile (Case I, \(P_L=10m\))

4. PILE-CAP RESISTANCE

The pile cap resistance of three different position of cap (case 1-3) for the pile length \(P_L\) of 10 m are shown in Figures 3-5.

Fig. 3: Load Vs. Displacement for Case 1 and \(P_L=10m\) (Cap Resistance = 33.16 %)

Fig. 4: Load Vs. Displacement for Case 2 and \(P_L=10m\) (Cap Resistance = 34.08 %)

Fig. 5: Load Vs. Displacement for Case 3 and \(P_L=10m\) (Cap Resistance = 35.43 %)

The pile cap resistance of the pile length \(P_L\) of 15 m for three different Cases 1-3 are shown in Figures 6-8.

Fig. 6: Load Vs. Displacement for Case 1 and \(P_L=15m\) (Cap Resistance = 36.02 %)
Similar fashion of results has observed in case of pile length of 15m for different cases. But the amount of cap resistance is quite more for same position of pile cap in case of 15 m longer pile compare to the 10 m pile. These are 36.02 %, 37.60 % and 39.98 % for similar position of pile cap as 10 m long pile. It is obvious as pile length contributes the lateral resistance.

The trend of results computed with the developed finite element model is in good agreement with the results presented by El-Garhy et al. (2009). Further Mokwa (1999) concluded that approximately 50 % of the overall lateral resistance of the pile group foundations governed by pile cap. In this analysis, it is observed that more or less about 50 % of the overall resistance is governed by the pile cap.

5. CONCLUSION

It is observed in case of single pile also, the pile cap has a good contribution against the lateral load. The pile cap resistance increases as the depth of pile cap below ground level increases. The length of pile plays a vital role in case of the lateral resistance of pile. It can be concluded that the pile cap resistance increases as the length of the pile increases. Thus both, pile cap elevation below the ground surface and the pile length are the influencing parameter of pile cap resistance under the lateral load.

REFERENCES


