LATERAL RESPONSE OF PILE UNDER INDIRECT LOADING DUE TO ADJACENT EXCAVATIONS

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ABSTRACT: The effect of indirect loading due to adjacent excavations on the lateral response of pile in sandy soil is brought out in the paper through numerical analysis by using PLAXIS3D software. In the numerical analysis, the pile was treated as a linear elastic material and the behavior of soil was idealized by using the Mohr-Coulomb model. The indirect loads on the piles are presented as a function of some of the key parameters like depth of excavation and pile location from the excavation face, which are of prime interest to designers. The numerical results in terms of lateral deflections and maximum bending moments in the pile sections with respect to both direct and indirect loads are presented in the paper.

INTRODUCTION
Pile foundations are normally designed to support ‘direct loads or active loads’, which are directly applied to the pile cap by a structure. However, with the increased construction activity in the form of excavations, road embankments, tunneling etc., piles are also subjected to ‘indirect loads or passive loads’ induced from ground movements. One of the main design constraints in this case is to prevent or minimize damages to the pile supported buildings due to indirect loadings. Although an excavation will cause both vertical and lateral soil movements, lateral soil movement is considered to be more critical, as piles are usually designed to sustain significant vertical loads. In contrast, lateral loads imposed on piles due to adjacent excavations induce an additional bending moments and deflection on the piles, which may lead to structural distress and even failure. Hence it is essential to enumerate the effect of indirect loading on the lateral response of piles to evaluate the performance and integrity of pile foundations.

Various researchers [1, 2] have attempted to study the behavior of piles due to lateral soil movements using a 2-d plane strain analysis. The response of piles due to adjacent excavation was studied in two phases [3]. In the first phase, the soil movements due to excavations were predicted using 2-d finite element model and in the second phase, pile responses were analyzed using the boundary element method. A few researchers [4,5] have attempted to study the response of piles adjacent to an excavation by assuming uniform soil movement profiles using 3-d finite element method. Researchers have also studied the effect of vertical load on the lateral response of both short and long piles in sandy and clayey soils [6, 7]. The following important gaps were identified in the subject area of the present paper. Numerical analyses have performed by assuming that the induced lateral ground movements on the piles due to various practical cases are uniform in nature. However, in real field situations the induced ground movements in the piles due to various cases are non-uniform in nature. Also, analyses have performed in two stages i.e., prediction of ground movement due to excavation in first stage and incorporating the predicted ground movement for pile analysis separately in the second stage. However, in reality these two analyses are always coupled in nature.

In this paper, an attempt has been made to bridge the identified gap in the area of lateral response of piles. The pile foundation subjected to indirect lateral loads due to various practical cases are normally superimposed with direct lateral loads. Therefore, the lateral response of piles under both direct and indirect loading has been investigated by performing a series of coupled analyses using PLAXIS3D software. The numerical results in terms of bending moment and lateral deflections with respect to various parameters such as normalized depth of excavation (H/Bo) and pile location from the excavation face (Xp) in sandy soil has been discussed. Critical observations on the results have also been made with respect to practical design point of view. The limiting location of the piles up to which indirect lateral loads need to be considered in the design has also been brought out in the following sections.

NUMERICAL ANALYSIS
The 3-d finite element based PLAXIS3D software has been used to analyze soil-pile interaction under indirect loading. In the analysis, the pile is assumed to be linear elastic and the soil is treated as an elasto-plastic material, obeying Mohr-Coulomb failure criterion. The sheet pile wall is assumed to be linear isotropic material. Fig. 1 shows the definition of the problem. The finite element mesh has been generated by using 15-noded wedge element for soil continuum, volume pile for the pile and vertical wall element for the sheet pile wall. In the mesh, all the vertical boundaries are fixed in the normal direction to their surface and free in other two direction representing rigid, smooth lateral boundaries. The bottom boundaries are fixed in all the three directions. For the sake of analysis, the following properties are considered.

Properties of sand: Unit weight (γ) - 18 kN/m³, Elastic modulus (E) - 20.0 MPa, Poisson’s ratio (μ) - 0.30,
Cohesion - 0.01 kN/m², Angle of internal friction (φ) - 30°, Lateral earth pressure coefficient (K₀) - 0.5 and Interface strength reduction factor (R) - 0.667.

Pile: Shape - circular, Length (Lₚ) - 15.0 m, Diameter (D) - 500 mm, Unit weight (γ) - 24.0 kN/m³, Elastic modulus (E) - 25 × 10^6 kN/m², Poisson’s ratio (μ) - 0.15.

Sheet Pile Wall: Unit weight - 78.5 kN/m³, Length – 13 m, Thickness (t) - 0.014 m, Elastic modulus – 1.8 × 10¹¹ kN/m², Shear modulus (G) - 9 × 10¹⁰ kN/m², Poisson’s ratio - 0.0.

In the numerical analysis, initially self weight analysis has been carried out to generate the in-situ stresses in the soil mass. Further analyses have been carried out in two phases. In the first phase, the piles were subjected to direct vertical and lateral loads of 1500 kN and 150 kN respectively then the sheet pile wall was installed. In the second phase, direct loading was remains constant while the soil layers were excavated from top to bottom in various steps with each step involves the removal of 1m and continued until the desired depth of excavation was achieved. Fig. 2(a) and 2(b) shows the 2-d and 3-d finite element discretization of the problem.

RESULTS AND DISCUSSIONS

Fig. 3 shows the lateral deflection along length of the pile due to both a direct lateral load of 150 kN and indirect lateral loads with respect to different depths of excavations. The pile deflection profiles as presented in the figure are pertaining to a pile located at a distance of 1 m away from the excavation. It can be seen from the figure that the maximum lateral deflections are occurring at top head of the pile in all the cases. Further, the maximum induced lateral deflections in the pile section due to indirect loads are increasing with increase in normalized depth of the excavations (Hₑ/Bₑ). Also, it is to be noticed that the lateral deflection profiles for piles under indirect loads are almost in line with the pile under direct lateral load for a shallow depth of excavations. However, it is different in the case of a deep depth of excavations say i.e., Hₑ/Bₑ beyond 0.3.
of bending moment profiles are almost same for the pile under both direct and indirect lateral loads. Further, the maximum bending moment induced in the pile section is observed to be increased with increase in normalized depth of the excavation (\(H_e/Be\)). The depth at which maximum bending moment occurred was at 2.1 m from the top of the pile head for all the cases. It indicates that the effect of indirect lateral load on the occurrence of the maximum bending moment is less significant. It can also be noticed that the point of zero bending moment is slightly moved down with increasing depth of excavations. This may be due to the fact that the depth up to which the mobilized passive resistance increases for pile under combined vertical and lateral loading is more than that of the pile under pure lateral loading [8]. In the present case, the pile was subjected to combined vertical and lateral loads prior to the application of indirect loading.

Fig. 4 Bending moment along the length of pile under direct and indirect lateral loads

**DESIGN PERSPECTIVE**

In the normal practice, piles are designed for vertical loads from the superstructure and are checked for the directly applied lateral loads and bending moments for an allowable deflections prescribed by the structural design codes. The allowable lateral deflections could be 5 mm to 12 mm for foundations of residential and industrial structures, which could even be relaxed up to 5 percent of the width of pile in case of the offshore structures [8]. In view of the same, the maximum lateral deflection and maximum bending moment induced on the piles due to indirect lateral loads are estimated with respect to the pile located at different distances (\(X_P\)) from the excavation face. For the sake of understanding, the maximum lateral deflection and maximum bending moment induced on the piles due to direct lateral load is also plotted in the same figure. The interest is mainly to investigate whether the pile designed for direct lateral load is safe against indirect load or not. Figs. 5 and 6 show the maximum lateral deflection and maximum bending moment induced on the pile under direct lateral loads and indirect lateral loads with respect to different normalized depth of excavations (\(H_e/Be\)).

Fig. 5 shows the variation of maximum lateral deflection of the pile corresponding to different distances of pile location (\(X_P\)) from the excavation face. It can be seen from the figure that the maximum lateral deflection of pile located at 10.0 m or more away from the excavation face is almost constant. It indicates that the effect of indirect loading on the pile response is less significant for the pile located beyond this limit. It can also be noticed that the intersection of lateral deflection curves for the pile under indirect loads and under direct loads indicates a clear demarcation on the governing criterion. This observation is almost similar for the pile under indirect loads with respect to different depth of excavations.

Fig. 5 Demarcation of response of the pile under indirect lateral loads with direct lateral loads based on maximum lateral deflection

![Fig. 5](image_url)

Fig. 6. Demarcation of response of the pile under indirect lateral loads with direct lateral loads based on maximum bending moment

![Fig. 6](image_url)
For structural design of piles, the bending moments developed in the pile section are important. The influence of indirect lateral loading on the bending moments developed in the pile section has been examined from the results obtained. Fig. 6 shows the variation of maximum bending moments for piles located at different distances from the excavation face. It can be seen from the figure that the effect of indirect loads on the variation of maximum bending moment in the pile section is almost negligible for the pile located at a distance of 10 m away and beyond from the excavation.

Table 1 Location of piles beyond which the pile designed for direct loading is safe against indirect loads

<table>
<thead>
<tr>
<th>Normalized depth of excavation (H_e/Be)</th>
<th>Safe limit of pile location (X_p) based on allowable deflection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5 mm</td>
</tr>
<tr>
<td>0.1</td>
<td>1.5</td>
</tr>
<tr>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>0.3</td>
<td>4</td>
</tr>
<tr>
<td>0.4</td>
<td>5</td>
</tr>
<tr>
<td>0.5</td>
<td>&gt;25</td>
</tr>
<tr>
<td>0.7</td>
<td>&gt;25</td>
</tr>
</tbody>
</table>

Further, in order to quantify the influence of indirect loading, the safe location of pile from the excavation face is estimated based on deflection criteria and are presented in Table 1. From the table, it is to be interpreted that if a pile under direct lateral load is designed for an allowable lateral deflection of 10 mm, the design is safe up to an excavation height (H_e/Be) of 0.2 even if the source is at very close vicinity (zero distance). However, if depth of the excavation (H_e/Be) increases to 0.3 and above, the design is safe only if the pile is located at a distance of 6.25 m away and beyond from the excavation face. The results from the maximum bending moment point of view as shown in Fig. 6 also substantiate these findings. In contrast, if the pile is designed for an allowable lateral deflection of only 5 mm then the effect of indirect loading is significant even at shallow depth of excavation. It is clear from the table that the design is safe if the pile is located at a distance of 5 m away and beyond from the excavation face for H_e/Be up to 0.4. However, if the depth of excavation increases to 0.5 and above then the design is safe only if the pile is located at distances beyond 25 m from the excavation face. Thus, it is essential that the piles should be designed by incorporating the effects due to possible indirect lateral loads.

CONCLUSIONS
The lateral response of single pile under indirect loading due to adjacent excavation in sandy soil has been investigated in the paper through numerical analyses. Based on the results obtained, the following conclusions can be drawn:

1. The lateral response of pile is highly sensitive to indirect loading due to adjacent excavations with respect to the depth of excavation (H_e/Be) and the pile location (X_p).
2. The effect of indirect lateral loading on the pile is to increase the pile deflection and bending moments up to considerable distances away from the excavation. The effects are severe particularly at deep depth of excavation (H_e/Be = 0.5) and extend even for the pile located beyond 25 m from the excavation face.
3. The piles that are designed for greater lateral deflections are more tolerant to additional forces induced on the piles due to adjacent excavations.
4. The results similar to those in Table 1 could be generated for particular cases in order to assess the sensitivity of a given pile to adjacent excavations.
5. In view of the increased construction activities, particularly in the urban areas, it is time to look into the current design practices, so that the effect of indirect load due to excavations can be counteracted to the possible extent.

REFERENCES