Soil Arching on Piles supporting Deep Excavations

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ABSTRACT: The use of contiguous pile walls as excavation support has also become common in engineering practices. The implementation of contiguous pile walls for deep excavation support is most suitable for cohesive soil where ground water table is below the excavation level. Numerical studies were carried out to study the failure mechanism and the effect of soil arching between the piles. Center-to-center distances between the piles were varied and parametric study in the soil arching behavior was carried out. The re-orientation of stresses in the proximity of piles supporting excavations into an arch shape causes reduction in horizontal stresses in the soil gap between the piles. This reduction in stresses can be effectively used in the application of piles with soil gap, as supporting system in deep excavations.

Keywords: Deep excavations; Soil Arching; Inverted Soil Arch; Soil Gap Ratio; Active Trapdoor mechanism

1. Introduction

In urban areas, the demand of deep excavations in the case of basements of high-rise buildings, tunnel stations, underground parking and other underground structures is progressively increasing over the years. Sheet pile walls and concrete diaphragm walls are popular forms for deep excavation supports in soft soil. Furthermore, soldier pile and lagging walls, reinforced concrete (cast-in-situ or prefabricated) retaining walls and jet-grout walls (or deep soil mixing) with anchors or struts are also being used as deep excavation support system. Various factors affecting the selection of deep excavation support system are size of excavation, ground water level, settlement of adjacent ground, soil properties and displacement criteria. Recent advancement in area of deep excavations is the replacement of traditional deep excavation support systems with contiguous piles (Keawsawasvong and Ukritchon, 2017; Gaba et. al. 2003). The application of contiguous pile walls for deep excavation support is most suitable for cohesive soil where ground water table is below the excavation level. The wall consists of discrete column piles that are typically installed into the ground before the excavation. The contiguous piles used in excavations can be designed with or without soil gap between the piles.

Handy (1985) considered two parallel, unyielding, rough vertical walls retaining a granular fill and described the trajectory of minor principal stresses as inverted arch. Many researchers (Evans 1983; Costa et al. 2009; Smith 2012; Iglesia et al. 2013; Wang et al. 2017) had carried out experimental studies to analyze trapdoor mechanism for both cohesive and cohesion less soils. Application of piles for deep excavation support resembles the active trapdoor mechanism, but in the horizontal direction. Many experimental and analytical studies were conducted by various researchers for the past few decades (Ito and Matsui 1975; Vermeer et al. 2001; Haema and Tanseng 2010; Richards et al. 2016; Keawsawasvong and Ukritchon 2017). Numerical studies were carried out to study the failure mechanism and the effect of soil arching between the piles.

2. Numerical Modeling

Numerical analyses were carried out using Plaxis 3D, in which the soil profile and laterally loaded piles are modeled in Mohr-Coulomb and linearly elastic non-porous material, respectively. 12 meters thick cohesive soil layer over a bed rock is modeled as shown in Figure 1. The ground water table is considered at a depth of 11m. Refined meshing is done on the retaining side of the pile wall as shown in Figure 2.

Excavation process was replicated numerically by an eight-phase process:

Phase 0 – Application of initial soil conditions.
Phase 1 – Installation of piles.
Phase 2 – Excavating up to 1m depth.
Phase 3 – Excavating up to 2.5m depth.
Phase 4 – Excavating up to 4m depth.
Phase 5 – Excavating up to 5.5m depth.
Phase 6 – Excavating up to 7m depth.
Phase 7 – Excavating up to 8.5m depth.
Phase 8 – Excavating up to 10m depth.
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Reinforced concrete piles of 0.8m diameter were used in numerical model. Three different soil gaps between the piles (S = 0.2m, 0.4m and 0.8m) were considered for analyses. For each case, eight-phase process was through 41 steps. For the comparison of results, three points (P, Q and R) were selected in each case, at a particular depth of d=7.5m (Figure 3).

2.1 Properties used in the numerical modeling
All soil parameters and values adopted for finite element model are summarized in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Soil</th>
<th>Bed rock</th>
<th>Pile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Mohr-Coulomb</td>
<td>Mohr-Coulomb</td>
<td>Linearly elastic</td>
</tr>
<tr>
<td>γ unsat (kN/m³)</td>
<td>17</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>γ sat (kN/m³)</td>
<td>19</td>
<td>24</td>
<td>-</td>
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<tr>
<td>Young’s modulus, E (kN/m²)</td>
<td>36 x 10³</td>
<td>45 x 10³</td>
<td>25 x 10⁹</td>
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<td>Poisson’s ratio, ν</td>
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<td>0.15</td>
<td>0.15</td>
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<tr>
<td>Cohesion, C’(kN/m²)</td>
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<td>-</td>
</tr>
<tr>
<td>Friction angle, φ’ (°)</td>
<td>32</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>Dilatancy angle, ψ (°)</td>
<td>4</td>
<td>5</td>
<td>-</td>
</tr>
</tbody>
</table>

2.2 Validation of the numerical modeling
Co-efficient of at-rest earth pressure, K₀

\[ K₀ = 1 - \sin \phi' \]  

(1)

For \( \phi’ = 32° \)

\[ K₀ = 0.47 \]

At 2m depth, the cartesian effective stress in horizontal direction, \( \sigma'_{xx} \)

\[ \sigma'_{xx} = K₀ \times \sigma'_{yy} \]  

(2)

The cartesian stress in X direction at a depth of 2m, obtained by numerical analysis (Phase 0) is depicted in Figure 4a.

3. Results and discussion
Figure 4 illustrates the soil arching mechanism at 2 meters depth on supporting piles with 0.8m soil gap. At phase 2 (Figure 4b), the formation of inverted soil arch can be evidenced. In the proceeding phases (Figure 4c and d), the depth of excavation will be below the cross section considered of 2 meters depth and thereby reduction of stresses in X direction can be observed in the space between the piles. The cartesian stress at the soil gap between the piles can drop down to even zero value. The re-orientation of stresses in the shape of an arch can be evidenced (for a particular case of 0.4 m soil gap at 2 meters depth) from Figure 5.
The change in cartesian effective stresses in X direction, at the points P, Q and R with the increase in number of steps or in the sequence of phases of excavation are shown in Figures 6, 8 and 10. The variation of corresponding cartesian strains are also depicted in Figures 7, 9 and 11.

In Figure 5, it can be observed that the major principal stresses re-orient to form an arch shape in the proximity of piles supporting excavations. This in turn causes the redistribution of stresses from the geostatic stress. The rotation of principal stresses cause the orientation of stresses in between the embedded piles in an arch shape in which the major principal stresses acting on the tangential direction and minor principal stresses on radial direction. This soil arching effect diminishes or completely arrests the flow of soil through the gap between the piles.
A general trend of reduction in stresses at P1, P2 and P3 throughout the excavation process is observed from Figures 6, 8 and 10. This behavior is due to the lateral deformation of piles used for the excavation support. However, it can be clearly noticed that the stresses at P, Q and R starts from around same value at the initial phase of excavation and reaches down to values within which the stress at P will be higher, followed by Q and then R at the final phase of excavation. This behavior clearly indicates the soil arching mechanism.

The soil arching mechanism can also be evidenced from Figures 7, 9 and 11; as the cartesian strains and point R at each case is higher than that at points Q and P. The soil arching mechanism in the lateral direction will be helpful in the application of piles as deep excavation support system. As the stresses at the soil gap between the piles drops down to a smaller value, contiguous piles used as excavation support can be designed with adequate spacing between them, provided the site conditions are favorable. Appropriate measures should be adopted for the drainage and dewatering at the site in view of long term stability of the structure.

4. Conclusions
Numerical analyses were carried out to study the role of soil arching on the stability of piles as deep excavation supporting system. Soil arching effect diminishes or completely arrests the flow of soil through the gap between the piles. Formation of inverted arch is observed in the horizontal cross section of the excavation side, below the depth of excavation at each stage. This inverted soil arch also partially prevents the flow of soil through the gap between the piles. The pressure will be relatively lesser and can reduce to even zero at the midway between the piles. This reduction in stress at the midway between the piles will be beneficial for the design of piles as excavation supporting system with spacing between them.

References