Stability analysis of Contiguous pile

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Abstract. Nowadays in modern construction, large-scale structures with greater heights that need deeper excavation are more popular. At present, the new structures from residential buildings to commercial complexes are keen on adopting basement floors for more underground utilities. These new structures with the need for basements are going for deeper excavation close to the existing buildings surrounding the proposed site of construction. In this case, understanding the behavior of soil profile based on load-bearing capacity, settlement, density, and angle of friction are important to safeguard the adjacent structures from being damaged. Very often deep excavations are supported by pile wall systems. In the literature, it appeared that pile walls are analyzed and designed for active and passive earth pressures. Recent investigations paved the way for my research to consider and implement the contiguous piles based on soil-structure interaction to eradicate soil sliding from the adjacent large buildings during the process of deeper excavation at the worksite. In the present study, the pile is analyzed by considering active and passive earth pressures using Rankine’s theory and Brinch Hansen’s technique respectively. Together with passive earth pressure, horizontal subgrade modulus is also considered using Terzaghi’s concept. With these forces, the stability of the pile is analyzed using the STAAD.Pro software. For parametric study three different pile diameters of 0.45m, 0.6m and 0.9m are considered. Deflections, shear force, and bending moment of the pile are computed. It is inferred that 0.9m diameter pile wall is stable for the given loadings.

Keywords: Contiguous pile, Embedded depth, Rankine’s theory, Brinch Hansen’s method, Terzaghi’s concept, STAAD.Pro.

1. Introduction

The construction sector has a particular set of challenges in urban environments. Urban locations have unique characteristics such as restricted movement, insufficient room for equipment, soil variability, change in the water table, foundation interaction and soil sliding. So, development of new structures has a negative impact on the neighbouring structures. As a result of heavy traffic and a shortage of area, civil engineers have been forced to dig deep into the soil to generate more floor area to satisfy rising space demands for amenities, parking, and the storage of building supplies. Therefore, the amount of deep excavations in the cities grows at an accelerating rate, so are the issues that come with their development. Deep retaining systems have been successfully installed in complex urban environments by overcoming construction constraints. Some of the pile walls used are Contiguous pile wall, tangent pile wall, secant pile wall and micro-pile wall system. The centre to centre spacing of piles is quite larger than the pile diameter in contiguous bored pile construction. Large spacing is
discouraged because it might cause soil to cave in via gaps. For secant bored piles the distance of the piles must be smaller than the diameter of the pile. When secant piling and diaphragm walling equipment are unavailable, tangent piles are employed. Deep excavation resisting systems usually fail due to active earth pressure. Of the several theories presented on active earth pressure Rankine’s theory possesses highest match to the PLAXIS analysis [1]. Precise assessment of earth pressure distribution influences stability, stresses induced and deformation of resisting system. Stability of contiguous pile wall as deep excavation supporting system [2] has been analysed by considering active forces on one side and passive forces on the other side by relatively fixing the embedment depth.

Deep excavations are very often supported by contiguous pile wall system. The choice of the system is more prevalent with depth of excavation, embedment length, type of soil and ground water table. Parametric study [3] on pile walls indicated that an increase in friction angle increases the shear strength within the soil and hence decrease in pressure on the retaining system. Also, with increase in unit weight of soil, vertical stress action on a soil mass increases influencing the lateral active stress to increase. It is also noted that up to certain depth of the pile with increase in height of pile wall, deformation of pile wall was reduced beyond which with increase in height of the pile, the deformation has increased and made it slender. In order to design proper retaining system in view of stability and strength criteria with contiguous piles, understanding the behaviour of soil with respect to the variable parameters of active, passive earth pressures and horizontal subgrade reaction for a pile are essential. The following points are noted for the present study, with few assumptions Rankine presented an expression for active earth pressure coefficient $K_a$ in terms of angle of shearing resistance $\varphi$ given by equation (1):

$$K_a = \frac{1 - \sin \varphi}{1 + \sin \varphi}$$

(1)

Active earth pressure

$$P_a = K_a \times \sigma_v$$

(2)

$\sigma_v$ is the vertical stress at any depth along the contiguous pile. Active earth pressure causes a moment in the contiguous pile at the bed level of excavation, which is presumed to be replaced by a lateral load at the tip of the pile. Correspondingly, ultimate resistance of pile to lateral loads can be carried out using Brinch Hansen’s method [5] has given by equation (3).

$$p_z = (p_{oz} \times K_{qz}) + C K_{cz}$$

(3)

Where,

$p_{oz} = $ Effective overburden pressure

$C = $ Cohesion of soil

$K_{qz} = $ Passive pressure coefficient for frictional components

$K_{cz} = $ Passive pressure coefficient for cohesive components

Lateral load which is presumed at the tip of the pile causes passive resistance in the embedded portion of the pile. Passive resistance developed will be opposed by the soil behind the pile horizontally. Horizontal force can be idealized as a spring of stiffness from horizontal subgrade reaction multiplied with tributary area of the pile. Estimation of horizontal subgrade reaction can be readily calculated by the formula available in the literature [6, 7]. Water table is at a deeper level and hence not considered. In the present study, active and passive earth pressures are converted into uniformly distributed load and assigned to the pile with horizontal subgrade reaction as spring of stiffness opposite to passive earth pressure for the stability analysis. Analysis was carried out using STAAD.Pro software with these forces. The model prepared has been treated as idealized modelling.

Most commonly used pile diameters are 0.45, 0.6, and 0.9 meters. The group piles are linked at the top by a capping beam, which facilitates for equal pressure distribution in piles. In densely populated urban areas, traditional retaining techniques may congest the surrounding land, leaving less space for operations, therefore contiguous piles are suitable. Contiguous piles reduce backfill ground movement, safeguarding surrounding structures, foundations, and boundary walls from the excavation detrimental impacts.
2. Geometrical conditions of pile wall

A cantilever Contiguous Pile Wall (CPW) is used in this investigation. The pile is modelled as a huge discrete circular concrete pile with active, passive earth pressures in opposite directions above and below foundation level with subgrade modulus. Three different pile diameters of 0.45, 0.6 and 0.9m are considered for a comparative study. Pile is modelled as linear elastic material of concrete with elastic modulus of $2.7386 \times 10^7$ kN/m$^2$ and with a density of soil as 16.1 kN/m$^3$. Centre to centre distance of piles maintained with a clear gap of 0.15m for three different piles of 0.45m, 0.60m and 0.90m are 0.60m, 0.75m and 1.05m respectively.

3. Loading considerations of pile wall

The total length of the pile is 13m. Foundation is at 6.8 meters below the current ground level and the embedded length is 6.2 meters. As a result, active earth pressure will operate on the wall up to 6.8 meters below the current ground level, while passive earth pressure will act in the opposite direction with the remaining 6.2 meters. In the embedded length of the pile wall passive pressure will be counter acted by the horizontal subgrade modulus of the soil. Active, passive pressures and subgrade modulus are assigned to the pile/pile wall based on the tributary area.

4. Methodology

4.1. Active Earth Pressure [4]

When discussing active earth pressure, Rankine Earth Pressure theory and Coulomb Earth Pressure theory are two relatively simple classical theories (among others) that are widely used an average value of $\phi$ is considered in all the calculations. In the present study, active earth pressure is estimated based on Rankine’s theory and are given in Tables 1 and 2. For the specific situation of a horizontal backfill surface, the Rankine active earth pressure coefficient is computed as given in equation (1). For loading on pile, the active earth pressure is multiplied with tributary area, i.e., width of the pile multiplied by unit length to obtain UDL (kN/m).

| Length of the pile measured from top (m) | Diameter of piles |
|----------------------------------------|-------------------|
|                                        | 0.45m  | 0.6m  | 0.9m  |
| 0.00-1.00                              | 0.000  | 0.000 | 0.000 |
| 1.00-2.00                              | 2.174  | 2.898 | 4.347 |
| 2.00-3.00                              | 5.414  | 7.218 | 10.827|
| 3.00-4.00                              | 7.560  | 10.080| 15.120|
| 4.00-5.00                              | 9.771  | 13.028| 19.541|
| 5.00-6.00                              | 12.012 | 16.016| 24.023|
| 6.00-6.80                              | 11.234 | 14.979| 22.468|

Table 1. Active Earth pressures values on single pile in kN/m

| Length of the pile measured from top (m) | Diameter of piles |
|----------------------------------------|-------------------|
|                                        | 0.45m  | 0.6m  | 0.9m  |
| 0.00-1.00                              | 0.000  | 0.000 | 0.000 |
| 1.00-2.00                              | 2.898  | 3.623 | 5.072 |
| 2.00-3.00                              | 7.218  | 9.023 | 12.632|
| 3.00-4.00                              | 10.080 | 12.600| 17.640|
| 4.00-5.00                              | 13.028 | 16.284| 22.798|
| 5.00-6.00                              | 16.016 | 20.019| 28.027|
| 6.00-6.80                              | 14.979 | 18.724| 26.213|

Table 2. Active earth pressure values on pile wall system in kN/m
4.2. Brinch Hansen’s and Brom’s theory[5]

The ultimate lateral resistance of short stiff piles may be calculated using Brinch Hansen’s technique and is given in Tables 3 and 4. The approach is uncomplicated which would be used on both uniform and multilayer soils. It can be applied on c-Φ soils. The pile can attain a stable strength by considering all the moments which are present above and below the point of rotation. The unit passive resistance for the depth ‘z’ underneath the ground level can be given by the equation (3). Average values of c-Φ are considered in the calculations.

All the terms were taken at the depth ‘z’. The K_q and K_c are related to depth ‘z’ and the pile diameter ‘B’ in the direction of rotation. K_q and K_c values to be used in equation (3) can be taken from figure 1 and figure 2. On each horizontal element total passive resistance is given by equation (4).

\[
p_x \times \frac{L}{N} \times B
\]

(4)

Figure 1 Brinch Hansen’s Coefficient K_q

Figure 2 Brinch Hansen’s Coefficient K_c

Table 3. Passive load by Brinch Hansen’s theory for single pile

| Length of the pile measured from top (m) | 0.45m (kN/m) | 0.6m (kN/m) | 0.9m (kN/m) |
|-----------------------------------------|--------------|-------------|-------------|
| 6.80-7.80                               | 206.933      | 252.512     | 325.048     |
| 7.80-8.80                               | 436.018      | 531.037     | 673.491     |
| 8.80-9.80                               | 565.670      | 814.506     | 906.720     |
| 9.80-10.80                              | 675.195      | 949.682     | 1102.557    |
| 10.80-11.80                             | 778.839      | 963.789     | 1284.050    |
| 11.80-12.80                             | 872.733      | 1090.128    | 1456.629    |
| 12.80-13.00                             | 551.823      | 1166.882    | 1556.921    |

Table 4. Passive load by Brinch Hansen’s theory for pile wall system

| Length of the pile measured from top (m) | 0.45m (kN/m) | 0.6m (kN/m) | 0.9m (kN/m) |
|-----------------------------------------|--------------|-------------|-------------|
| 6.80-7.80                               | 275.911      | 315.640     | 379.222     |
| 7.80-8.80                               | 581.357      | 663.796     | 785.740     |
| 8.80-9.80                               | 754.226      | 1018.132    | 1057.839    |
| 9.80-10.80                              | 900.259      | 1187.102    | 1286.317    |
4.3. Horizontal subgrade modulus[6, 7]

Broms (1981) proposed a subgrade reaction strategy based on the idealisation of the soil as a series of horizontal strata that offer spring supports. When compared to the equivalent cantilever approach, in which piles are approximated to cantilevers, this method is easy.

The relationship between the contact pressure \( p \) and the accompanying lateral displacement \( y \) of the contact face determines the horizontal subgrade reaction coefficient for a vertical pile. The displacement is caused by the neighbouring medium deforming with Elastic Modulus \( E_s \). Beyond a distance of 3B, displacements have almost no effect on the pile's local bending moment. As a result, if the pressure \( p \) acts on the elastic layer of thickness 3B, the displacement \( y \) may be calculated.

For piles embedded in stiff clay the value of horizontal subgrade modulus \( (k_{h1}) \) can be roughly assumed to be identical value of \( k_{s1} \) which denotes the basic value of coefficient of subgrade reaction for beams resting on the horizontal surface of the same clay. Because the horizontal displacement of the contact face between pile widths of 1 ft is considerably smaller than that of a strip with the same width on the surface of the clay, at equal pressure per unit of area, the error involved in this assumption is on the safe side. The value for a pile with width \( B \) in ft is given by the equation:

\[
k_{h} = \frac{1}{1.5B} k_{s1}
\]  

(5)

4.4. STAAD.Pro Modelling

A model has been generated for 13m length, of which 6.8m from the top is foundation level and 6.2m is embedment depth. 6.8m length is divided into 7 elements in which the top 6 elements are divided into 1m each & 7th element is 0.8m. The active loads are assigned as UDL to 6.8m length. The embedded length 6.2m length is divided into 7 elements of which the first element is 0.2m and the remaining 6 elements are 1m each. Passive earth pressure in terms of UDL is assigned from 6.8m to 13m. Active earth pressure below 6.8m to 13m is assigned in the form of spring with stiffness by multiplying the subgrade modulus with tributary area.

![Figure 3 0.9m diameter Single Pile](image)

Figure 3 represents the single pile with diameter 0.9m loaded with active and passive pressures. For accounting the horizontal subgrade modulus soil springs have been added to the pile at every 1m from toe to 6m from the bottom of the pile.
Figure 4 represents the deflection of 0.9m diameter pile with -81.05mm at top and 117.174mm at bottom.

Figure 5 represents group pile of 10 piles with diameter 0.9m loaded with active and passive pressures along with springs which are added as a support for the pile at every 1m from toe to 6m from the bottom of the pile. A cap beam of dimensions 0.9×0.9 m is placed above the pile connecting all the piles.
Figure 6 represents the deflection of 0.9m diameter contiguous pile wall with 135.681mm at bottom and -75.979mm at top.

5. Results

Figure 7 represents the comparison of deflection between three different diameter piles which are 0.45m, 0.6m and 0.9m. It is observed that the maximum deflections in the 0.45m, 0.6m and 0.9m diameter piles are 140.476mm, 102.451mm and 81.05mm respectively. Due to the economical condition and the deflection point of view pile diameter of 0.9m is selected because it is in the limit of allowable deflection.
Figure 8 Graph showing deflection along the length of pile wall for various diameters

Figure 8 represents the comparison of deflection between three different diameter piles which are 0.45m, 0.6m and 0.9m. It is observed that the maximum deflections in the 0.45m, 0.6m and 0.9m diameter piles are 175.403mm, 120.409mm and 75.979mm respectively.

6. Conclusions
- 0.9m diameter pile exhibits almost a linear pattern of deflection about the rotating point. This is due to high rigidity. Hence, 0.9m diameter pile may be adopted for the pile wall system.
- In view of the stability of piles 0.9m diameter piles exhibits lesser deflection at the top node and hence it is stable.
- Piles with 0.45m and 0.6m diameter have exceeded a deflection of 100mm and hence are unstable.

7. References
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