Lateral Bearing Capacity of Piles in Cohesive Soils Based on Soils' Failure Strength Control

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ABSTRACT
This paper presents the results of a series of numerical analysis carried out on piles in cohesive soils. Broms (1964a) proposed graphs to obtain ultimate lateral bearing capacity of such piles. However, the graphs do not cover all piles with different lengths. In this study, a finite difference program that is especially designed for piles is used. The investigations were carried out by varying the length and diameter of piles in three different kinds of clayey soils.

The objective of this study is to suggest a series of graphs to cover the range between long and short piles that Broms did not consider. Additionally, in Broms solution the effect of vertical loading on lateral bearing capacity of piles did not considered. In this study, the effect of vertical loading is also studied, and the suitable graphs are presented to simplify pile design procedures in cohesive soils.

Finally, a full-scale lateral pile–load test is used to verify the accuracy of the methodology developed.

KEYWORDS: Pile; Clay; Broms Method; Lateral Bearing Capacity; Finite Difference Program.

INTRODUCTION
Lateral loads and moments may act on piles in addition to the axial loads. Axial downward loads are due to gravity effects. Upward loads, lateral loads, and moments are generally due to forces such as wind, waves and earthquake. The allowable lateral load on piles is determined from the following two criteria:
1. Allowable lateral load is obtained by dividing the ultimate (failure) load by an adequate factor of safety.
2. Allowable lateral load is corresponding to an acceptable lateral deflection.

The smaller of the two above values is the one actually adopted as the design lateral load.

Methods of calculating lateral resistance of vertical piles can be broadly divided into two categories:

1. Methods of calculating ultimate lateral resistance.
2. Methods of calculating acceptable deflection at working lateral load.

Terzaghi (1955) was an attempt to rationalize the pile resistance by using a variable passive coefficient, $K_{pm}$, which is a function of the mobilized angle of shearing resistance. In 1960’s, ultimate lateral resistance approaches for rigid piles by assuming that the full passive Rankine earth pressures were mobilized. In the method proposed by the Brinch Hansen (1961), the pile is assumed to rotate about a single point, the ultimate lateral load is calculated and the shearing force and bending moment diagrams are drawn. Broms (1964a) presented methods to determine the ultimate lateral load in cohesive and cohesionless soils. Kasch et al. (1977), state that using Rankine’s passive states will result in a very conservative solution. Reese (1977) developed a computer program that widely used to predict the performance of piles subjected to lateral loading. This program solves differential equation derived on the assumption that pile is linearly elastic and that the soil reaction may be represented as a line load. In recent years, extensive research and developments have been undertaken to predict theoretically the behavior of laterally loaded piles in clayey soils (Poulos and Davis, 1980; Reese, 1984; Brown and Shie, 1991 and Liang et al., 1998). Nowadays Broms solution is widely used for calculation of lateral bearing capacity of piles because of its simplicity. In this research the authority and accuracy of Broms solution in various soil and pile condition proceed by use of Allpile finite difference program and a series of graphs are presented to computation of lateral bearing capacity of pile in cohesive soil based on finite difference analysis.

**SCRUNITY OF BROMS METHOD**

Broms (1964a) presented his theory based on earth pressure for calculating lateral resistance of vertical piles, but simplifying assumptions are made for distribution of ultimate soil resistance along the pile length. He divided piles into two groups, Short rigid and long flexible piles are considered separately. The criterion for short rigid piles is that $L/T \leq 2$ or $L/R \leq 2$. Where:

$$T = \left( \frac{E'I}{n_h I} \right)^{1/5}$$  \hspace{1cm} (1)

$$R = \left( \frac{E'I}{k_h} \right)^{1/4}$$  \hspace{1cm} (2)

“$E’$” is modulus of elasticity of pile material, “$I’$” moment of inertia of pile section, “$n_h$” constant of modulus of sub grade reaction, $k_h = n_h x$.

The criteria for long flexible pile will be $L/T \geq 4$ or $L/R \geq 3.5$, as applicable. Broms graphs are shown in Figure 1.
The advantages of this theory are:
1. Applicable for short and long piles.
2. Considers both purely cohesive and cohesion less soils.
3. Considers both free-head and fixed-head piles that can be analyzed separately.
However, this method suffers from disadvantages that:
1. It is not applicable to layered system.
2. It does not consider $c\cdot \phi$ soils.

There are some more problems in this method, which we will discuss later.
In this study the Allpile finite difference program is used which is especially designed for piles. The investigations were carried out by varying the length of piles. Also different combinations of lateral force and moment are used. Different diameters of piles are also used to investigate its effect. All of these analyses were carried on three different kinds of clayey soils (soft, medium and hard clay). One of Broms solution deficiencies is that he does not consider effect of vertical loading on lateral bearing capacity of piles. In this study we consider this effect. The objective of this study is to suggest a series of graphs to simplify the procedure of pile design in cohesive soils.

**GEOMETRY OF THE MODEL**

The geometry of a typical finite difference model adopted for the analysis is shown in Figure 2. Finite difference analyses were carried out by applying horizontal loads on top of pile. To simulate applied moment just as Broms did, an extra length on top of pile is considered.

**Figure 1:** Ultimate lateral load capacity of short and long piles in cohesive soils; (a) Short pile, (b) long pile (Broms, 1964a).
Figure 2: Geometry of model

Table 1, presents the different diameters of pile that is used to investigate pile diameter influence on lateral bearing capacity of pile.

<table>
<thead>
<tr>
<th>B (m)</th>
<th>0.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>B (m)</td>
<td>0.80</td>
</tr>
<tr>
<td>B (m)</td>
<td>1.00</td>
</tr>
</tbody>
</table>

MATERIAL PROPERTIES

In this study, five material parameters were required to specify the soil model in each analysis, including “cohesion” or undrained shear strength $c_u$, modulus of subgrade “$K$”, strain at 50% deflection “$\varepsilon_{50}$”, unit weight of the soil “$\gamma$” and Young’s modulus of pile “$E$”. The material properties adopted in the analyses for soft, medium and hard clay are presented in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Soft clay</th>
<th>Medium clay</th>
<th>Stiff clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_u$ (kN/m$^2$)</td>
<td>18</td>
<td>39</td>
<td>72</td>
</tr>
<tr>
<td>$K$ (kN/m$^3$)</td>
<td>8143</td>
<td>27145</td>
<td>135724</td>
</tr>
<tr>
<td>$\varepsilon_{50}$ (%)</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma$ (kN/m$^3$)</td>
<td>16</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>$E$ (kN/m$^2$)</td>
<td>20 685 000</td>
<td>20 685 000</td>
<td>20 685 000</td>
</tr>
</tbody>
</table>
Material properties which are used are based on software recommendations and are in agreement with experimental evidence.

**EFFECT OF SOIL STIFFNESS ON ULTIMATE LATERAL BEARING CAPACITY**

At first, for considering a wide range of clayey soils a series of analyses have done on three different clays with different $e/B$ ($e$ is free distance over the soil surface and $B$ is pile diameter) and varying $l/B$ ($l$ is the length of pile), and the obtained results are compared with Broms graphs (Figure 3). In order to consider a range of different combinations of loads and moments we consider four ratios, which are $e/B = 0, 1, 2, 4$. In this stage it is resulted that Broms assumption on ultimate resistance is over estimate. He has assumed that the ultimate resistance of clays is $9BC_u$, but the results show that the soil will collapse much sooner, (see Figure 3).

**Figure 3:** Effect of soil stiffness and comparison with Broms method
For (a) $\frac{e}{B} = 0$, (b) $\frac{e}{B} = 1$, (c) $\frac{e}{B} = 2$ and (d) $\frac{e}{B} = 4$.

This analysis verified that pile in stiffer clay have higher ultimate lateral bearing capacity and with increase of clay stiffness, the ultimate lateral resistance increases and curves go toward Broms curve. In order to cover a range of usual pile lengths we consider different ratios, which are $l/B = 4, 6, 8, ..., 20$. In this approach piles which are not in Broms category (piles between short and long piles) can now be considered. A comparison between Broms curves and results of finite difference analysis is shown in Figure 4. Due to obtained results it can be concluded that the Broms method is over estimate.

**Figure 4:** Comparison between Broms curves and result of finite difference analysis (Broms, 1964a ; Allpile finite difference program)

**EFFECT OF PILE DIAMETER ON LATERAL RESISTANCE**

In order to present more general design graphs, in next step a series of analysis was carried out on pile with different diameters to investigate its influence, (see Figure 5). As it is shown, diameter dose not change the normalized ultimate lateral bearing capacity significantly.
Figure 5: Effect of pile diameter
CONSIDERATION OF VERTICAL LOAD

In previous analyses just as Broms method the vertical load did not consider. But to make our graphs more general, and also to investigate the influence of vertical load on ultimate lateral bearing capacity, we consider it. In this stage, in every analysis, at first the ultimate vertical bearing capacity is obtained by Allpile for $e/B = 0$, then by use of a factor of safety equals 3 the allowable vertical load are applied and finally the ultimate lateral bearing capacity of pile is determined, (see Figure 6). The result shows that the ultimate lateral load will decrease due to vertical load. So a lot care to choose the ultimate lateral bearing capacity of a pile should be taken.

![Figure 6: Effect of vertical load for $e/B = 0$.](image)

VALIDATION OF THE ANALYSIS RESULTS

In order to verify the presented graphs based on finite difference analysis, the results are compared with observed pile behavior at full scale laterally loaded pile test. Dunnivant and O’Neill (1986) conducted static lateral loading tests on steel pipe pile at the University of Houston. The soil deposit at the test site was consisted of submerged over consolidated clay which is classified as CL to CH. Pile geometry is shown in Figure 7.
Shear strength profiles were developed from undrained triaxial compression tests, cone penetrometer soundings, and field vane shear tests. The shear strength generally increased with depths, and ranged from 50 kPa to 200 kPa. In this paper the shear strength of Houston test site soil was selected 100 kPa in accordance to the value that taken by T. D. Smith (1983) in analysis of single piles subjected to static lateral load. Average unit weight of soil at Houston test site was between 19.8 kN/m$^3$ and 20.9 kN/m$^3$. At present study the Houston pile is modeled by Allpile software and the lateral bearing capacity of this pile is determined.

Good agreement is observed between measured and computed ultimate lateral loading capacity in Houston test, a comparison between result of this study and Broms solution is presented in Table 3.

A great difference is also exists between the Broms method solution and the full scale test results.

**Table 3:** Comparison between measured ultimate lateral bearing capacity of pile and full scale test.

<table>
<thead>
<tr>
<th>Test location</th>
<th>$Q_{ult}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full scale test</td>
<td>1330</td>
</tr>
<tr>
<td>Broms method</td>
<td>3644</td>
</tr>
<tr>
<td>Allpile</td>
<td>1786</td>
</tr>
</tbody>
</table>

**CONCLUSION**

A series of numerical analysis has been carried out to evaluate the ultimate lateral bearing capacity of a pile in cohesive soils. The study primarily aimed at presenting design graphs which they can cover all piles with different lengths, and also checked the failure criteria which Broms has proposed. Due to obtained data the following results can be concluded:

1. The soil collapse much sooner than that Broms assumed and his assumption is overestimated.
2. With increase of clay stiffening, the ultimate lateral resistance of pile increase and the curves go toward Broms curve.
3. The effect of pile diameter was studied and it was concluded that the pile diameter would not significant effect on normalized ultimate bearing capacity.
4. Vertical allowable load applied on pile and presented more general graphs. It is shown that the axial load decrease ultimate bearing capacity and a lot care to choose the ultimate bearing capacity of pile should be taken.
5. The computed ultimate lateral capacity of a tested pile in Houston University is modeled with Allpile and compared with in situ full pile test results. It is shown that the Allpile results have a good agreement with in situ test result. The great difference is also exists between the Broms method solution and the full scale test results.

REFERENCES


