Ultimate Lateral Load of a Pile in Soft Clay under Cyclic Loading

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ABSTRACT: In this paper, the ultimate lateral resistance of a long, flexible, unrestrained vertical pile in soft clay is computed under cyclic loading condition using p-y curves. A new method for the construction of p-y curves is proposed. The comparison of calculated results of the proposed method with the field test results reported by Matlock (1970) shows a good agreement. An iterative analysis is employed with secant modulus approach using a matrix method known as moment area method developed by Sawant and Dewaikar (1994). The load-ground line displacement relationship is obtained for different load eccentricities, number of cycles and pile diameters using the proposed p-y curves. Ultimate lateral load is computed from the log-log plot of ground line displacement and applied load and the effect of number of load cycles on the ultimate lateral load resistance is investigated for various pile diameters and load eccentricities.

1 Introduction

Piles in the offshore environment are frequently large and in quite a few situations, driven into soft saturated clay, which exhibits highly non-linear stress-strain behavior, even at low levels of applied loads. Cyclic lateral loading is an aspect of the problem that introduces additional complexity and is encountered in offshore foundations as well as other applications.

Amongst limited research works in this field, the major contributions are made by Matlock (1970), Idriss et al. (1978), Poulos (1982), Vucetic et al. (1988), Grashuis et al. (1990) and Georgiadis et al. (1992). A brief review of these works indicates that the degradation of the pile soil system under lateral cyclic loading mainly depends upon the following parameters: i) reduction in soil modulus and undrained shear strength, ii) number of cycles, iii) cyclic load level (ratio of cyclic load to the lateral static ultimate pile capacity, in case of load-controlled mode) and iv) cyclic displacement level (ratio of cyclic displacement applied at the pile head to the external pile diameter, in the case of displacement controlled mode).

As pointed out by Poulos (1982), the degradation is mainly due to

1) Partial to zero dissipation of excess pore water pressure generated during cyclic loading in progress,
2) Destruction of inter-particle bond with particle realignment and
3) Rearrangement and gradual accumulation of permanent plastic deformation around pile.

Over the past several years, considerable advances have been made in understanding the behavior of soils during cyclic loading. In order to predict the behavior in a reliable manner, a new degradation model for one-way cyclic lateral loading on piles in soft clay is proposed and is incorporated with the hyperbolic p-y curve for static loading.
proposed by Dewaikar and Patil (2005).

An iterative procedure is adopted to perform a parametric sensitivity analysis and the effect of cyclic lateral load on deflection is studied. Based on the lateral deflection at the end of first cycle (static load), empirical relations were established for strength degradation and gap effect, degradation model is assumed and the p-y curve is modified. The cyclic load analysis is carried out using the static analysis program idealizing the soil by modified p-y curve, which considers the effect of number of cycles, degradation in soil strength and magnitude of cyclic lateral load. The allowable lateral deflection of pile top is taken as 20% of the pile diameter and load values corresponding to this deflection level are computed for both static and cyclic conditions. Response of pile under one-way cyclic lateral loading is studied using these load values for varying number of load cycles, load eccentricities, pile diameters and pile embedment lengths.

2 Proposed method of analysis

For computing moment, rotation and deflection in respect to a long, flexible and unrestrained pile in cohesive soil, a non-linear analysis is performed. The proposed method of analysis is briefly described as follows.

2.1 Initial Tangent Modulus

In the analysis, the initial soil modulus, $E_s$, is taken as increasing with depth according to the expression suggested by Poulos and Davis (1980).

$$E_s = \eta h z$$

(1)

Where, $z$ represents depth below ground surface and $\eta h$ represents coefficient of soil modulus variation with depth. It is taken as 1800kN/m$^3$, average of 160-3450kN/m$^3$ suggested by Reese and Matlock (1956) for soft normally consolidated clays.

2.2 Development of p-y curves

For the validation purpose, analysis is performed using cyclic p-y curves developed by Matlock (1970), as shown in Fig. 1.

![p-y curve for soft clay under cyclic loading conditions, Matlock (1970)](image)
Where,

- $p_u =$ ultimate soil resistance
- $x =$ depth at which the p-y curve is constructed
- $p =$ soil resistance
- $y =$ deflection
- $y_{50} =$ deflection at one half the ultimate soil resistance
- $x_r =$ transition depth

2.3 Method of Analysis

The moment area method developed by Sawant et al. (1994) is used here for analysis. In this matrix method, the pile is discretized into small segments (150 nos.) of equal length and at the center of each segment, a node is considered. For each node, a p-y curve is developed. Over each segment the soil reactive pressure is assumed to be uniformly distributed. The problem then becomes identical to that of a vertical beam subjected to a load at its top and reactions at the nodes, which correspond to the soil pressures. Using conventional beam theory, equations are formulated for the evaluation of the unknown nodal displacements including the displacement and rotation at the pile head. One advantage of the moment area method is that, no assumption is required to be made regarding soil modulus variation with depth. For the analysis, the secant modulus approach is used in which the applied predetermined load is analyzed repeatedly.

An iterative scheme is employed in the nonlinear analysis with secant modulus approach, using the moment area method. First, the analysis is carried out with an assumed value of the soil modulus, usually the initial tangent modulus values as suggested by Poulos and Davis (1980). In the next analysis, the assumed value of soil modulus $E_s$ is revised ($E_s = p/y$) to become consistent with the evaluated deflection. The procedure is repeated until the calculated deflections between two successive analyses vary within a prescribed tolerance limit ($10^{-7}$m).

3 Validation of proposed method of analysis

A program is developed using C language, to facilitate the validation. Results of proposed method of analysis are compared with theoretical results given by Matlock (1970) as shown in Fig. 2, which are in close agreement. Maximum difference is of the order of 1% to 2%. So this method of analysis is used for further computations.

![Figure 2: Comparison of moments along the pile length (for load =35.6kN) for cyclic loads](image-url)
4 Matlock’s (1970) field test data

Matlock carried out field tests on a long, flexible, unrestrained vertical pile of 0.324m diameter with 12.802m length, embedded in soft clay at Sabine in Texas, with undrained shear strength 14kPa and submerged unit weight of 7.85kN/m³.

5 A New degradation model

Degradation of soft clay such as that found in many marine deposits during cyclic loading is well documented in numerous studies (Vucetic, 1988; Matasovic and Vucetic, 1992). The cyclic strength degradation of soil is implemented by using an exponential function that models the decreasing soil strength as a function of number of cycles. Experimental evidence for this type of strength degradation has been reported by Heerama (1979) and Smith (1987). Based on these finding, a degradation model is proposed as a function of number of load cycles, ratio of ground line deflection at mud line to 20% of the pile diameter and 10% of the ratio of elasticity modulus of soil to the undrained shear strength. The proposed expression is as per Equation 2.a.

\[
p_{uN} = p_u \left[ 1 - A \left( 1 - N^{-\frac{\Delta}{0.2b} \frac{E}{c_u}} \right) \right]^{0.1} (2.a)
\]

\[
\eta_{hN} = \eta_h \times N^{-B \times 0.5} (2.b)
\]

Where,

- \( p_{uN} \) is the soil resistance after N number of cycles
- \( p_u \) is the soil resistance for first cycle of load
- Parameter A defines the residual soil strength level after an infinite number of cycles and is taken as 0.7 since the residual soil strength after an infinite number of cycles results in at least 30% of the initial strength value (Grashuis 1990)
- \( \Delta \) is the ground line deflection under the applied load
- \( b \) is the external diameter of the pile
- \( \frac{E}{c_u} \) is to be selected from Table 1, based on the soil conditions (Skempton 1951)
- \( y \) is the pile deflection at each spring level
- \( \eta_h \) is the coefficient of subgrade reaction for first cycle of load
- \( \eta_{hN} \) is the coefficient of subgrade reaction at N cycles of load
- \( B \) is empirical constant derived after various trials and is taken as 0.0273 (Little and Briaud 1988)

5.1 Table 1. Typical soil parameters for soft clay (Skempton, 1951)

<table>
<thead>
<tr>
<th>Consistency of clay</th>
<th>( \varepsilon_{60} )</th>
<th>( \frac{E}{c_u} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td>0.020</td>
<td>50</td>
</tr>
<tr>
<td>Medium</td>
<td>0.010</td>
<td>100</td>
</tr>
<tr>
<td>Stiff</td>
<td>0.005</td>
<td>200</td>
</tr>
</tbody>
</table>

- \( E \) – elasticity modulus of soil
- \( c_u \) – undrained shear strength

6 Development of p-y curve

The following static p-y curve proposed by Dewaikar and Poonam (2005) was found to fit remarkably well with the field test data points given by Matlock (1970).
\[ p = \frac{y}{1 + \frac{y}{E_s p_u}} \]  

Equation 3 is modified by incorporating the degradation model (Equations 2.a & 3) for cyclic loading conditions. The cyclic p-y curve which fulfills the features of cyclic behavior is as follows:

\[ p = \frac{y}{1 + \frac{y}{E_s N p_u}} \]  

6.1 Validation of the proposed model

Analyses are performed as explained above (Section 2) using the proposed p-y curve (Eq. 4). Results are compared with field test results reported by Matlock (1970), as shown in Fig. 3.

Results are in very good agreement with the field test data, the difference is only of the order of 2\% to 3\% where as the difference between computed values using the Georgiadis (1992) cyclic p-y curves with field test data is of the order of 30 to 50\%. The proposed model is used for further computations, to calculate the ultimate lateral load.

7 Method of calculating ultimate lateral load

From the analysis, pile top deflections are obtained for various cyclic loads applied at an eccentricity, e from the ground surface. Computations are carried out for various load eccentricities, pile diameters and number of cycles.

The relationships between applied cyclic loads and pile top deflections are obtained and plotted on log-log scale for various cases as shown in Figs. 4 to 20. Then, two straight lines of different slopes passing through most of the points are identified. The intersection of these two lines gives the lateral load capacity, \( P_u \) (Indian Standard Code of Practice in Soil Engineering, Method of Load Test on Soils - IS 1888: 1988). As seen from these figures, points of higher loads lie on a straight line. But for points corresponding to lower loads, the best-fit line is drawn.
Fig 4 D=0.3m
Fig 5 D=0.6m
Fig 6 D=0.9m
Fig 7 D=1.2m
Fig 8 D=1.5m

Figs 4 to 9 Computation of ultimate lateral load capacity of a pile with load eccentricity 0.0 m and embedment length 30.0m in soft clay at 100 number of load cycles with change in pile diameter
Figs 9 to 13 Computation of ultimate lateral load capacity of a pile of diameter 0.6m and embedment length 30.0m in soft clay at 100 number of load cycles with change in load eccentricity.

Figs 14 to 19 Computation of ultimate lateral load capacity of a pile of diameter 0.6m and embedment length 30.0m in soft clay at varying number of load cycles.

Table 2 Variation of lateral load capacity of pile with pile diameter

<table>
<thead>
<tr>
<th>SR.No.</th>
<th>Pile Diameter (m)</th>
<th>$P_u$(kN)</th>
<th>$P_{0.2D}$(kN)</th>
<th>$P_u / P_{0.2D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>39.96</td>
<td>44.83</td>
<td>0.89</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>148.97</td>
<td>166.30</td>
<td>0.89</td>
</tr>
<tr>
<td>3</td>
<td>0.9</td>
<td>314.80</td>
<td>356.10</td>
<td>0.88</td>
</tr>
<tr>
<td>4</td>
<td>1.2</td>
<td>543.97</td>
<td>611.30</td>
<td>0.89</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>845.34</td>
<td>959.10</td>
<td>0.88</td>
</tr>
</tbody>
</table>
Table 3 Variation of lateral load capacity of pile with load eccentricity

| SR.No. | Load eccentricity (m) | $P_u$ (kN) | $P_{u0.2D}$ (kN) | $P_u/P_{u0.2D}$ |
|--------|-----------------------|------------|-------------------|----------------|----------------|
| 1      | 0.0                   | 145.93     | 166.30            | 0.88           |
| 2      | 5.0                   | 83.15      | 93.10             | 0.89           |
| 3      | 7.5                   | 68.35      | 75.95             | 0.89           |
| 4      | 10.0                  | 56.76      | 64.06             | 0.88           |
| 5      | 12.5                  | 49.38      | 55.36             | 0.89           |

Table 4 Variation of lateral load capacity of pile with number of load cycles

| SR.No. | Number of cycles | $P_u$ (kN) | $P_{u0.2D}$ (kN) | $P_u/P_{u0.2D}$ |
|--------|------------------|------------|-------------------|----------------|----------------|
| 1      | 1                | 184.07     | 207.50            | 0.88           |
| 2      | 5                | 170.12     | 190.97            | 0.89           |
| 3      | 25               | 157.37     | 176.83            | 0.89           |
| 4      | 50               | 152.70     | 171.31            | 0.89           |
| 5      | 100              | 148.57     | 166.30            | 0.89           |
| 6      | 200              | 143.51     | 161.25            | 0.89           |

Fig 20 Variation of ultimate lateral load of a pile of embedment length 30.0m at 100 number of load cycles with change in pile diameter (e=0.0m)

Fig 21 Variation of ultimate lateral load of a pile of diameter 0.6m and embedment length 30m at 100 number of load cycles with change in load eccentricity.

Fig. 22: Degradation of ultimate lateral load of a pile of diameter 0.6 m and embedment length 30.0m in soft clay with increasing number of cycles (e=0.0m)

8 Results and discussion

The computation of ultimate lateral load capacity of flexible unrestrained piles in cohesive soils is performed considering pile with embedment length as 30.0m and with diameters 0.3, 0.6, 0.9, 1.2 and 1.5m. Load eccentricity is taken as 0.0, 5.0, 7.5, 10.0 and 12.5. Analysis is carried out with number of load cycles as 1, 5, 25, 50, 100 and 200. The results are tabulated in Tables 2 to 5.

In the first case, ultimate load capacity is calculated with embedment length as 30.0m and with varying diameters. Load eccentricity is taken as zero in this case. The analysis is carried out for 100 number of load cycles. Results are tabulated in Table 2. A significant variation in ultimate lateral load capacity with change in pile diameter is observed;
when the diameter is increased to 5 times, increase in lateral capacity is 20 times the initial value. Computations are as shown in Figs. 5 to 9 and the variation is as shown in Fig.21.

In the second case, ultimate load capacity is calculated with embedment length as 30.0m and with diameter as 0.6m. Load eccentricity is taken as varying from 0 to 12.5m. The analysis is carried out for 100 number of load cycles. Results are tabulated in Table 3. Decrease in ultimate lateral load capacity by changing the load eccentricity from 0.0 to 12.5m is 66%. Computations are as shown in Figs. 10 to 14 and the variation is as shown in Fig.22.

Computation of ultimate lateral load capacity of a pile of diameter 0.6m and embedment length 30.3m number of cycles increasing from 1 to 200 is carried out as shown in Figs. 15 to 20. Degradation of ultimate lateral load with increasing number of cycles is as shown in Fig. 22. Initially degradation is very high for a first few cycles. From one to five cycles the degradation is of the order of 8% and for the next 20 cycles, it is of the order of 7%. For the next 25 cycles it is 3%. After that, degradation rate is very less compared to the initial degradation rate. For the next 50 cycles it is 6% and then reaching equilibrium after a large number of load cycles. From 100 to 200 cycles, degradation is only of 3%, which is very less compared to initial degradation rate.

As no other method or field test data is available in literature to validate this method, the results are compared with the load values corresponding to 0.2D deflection at pile top. The ratio of ultimate load to the load corresponding to 0.2D deflection (P_u/P_u0.2D) is calculated. It is clearly seen from the tabulated results (Tables 2 to 4) that, this ratio is almost constant in all the cases considered. From this it can be concluded that, it is possible to compute the ultimate load under cyclic loading conditions using this new technique as the trend of variation of ultimate load with diameter, load eccentricity and number of cycles is same as that of the variation of load corresponding to 0.2D deflection. The results obtained using this technique is on lower side as compared to the load corresponding to 0.2D deflection. Therefore, the method can be safely used for the ultimate load computations under cyclic loading conditions.

9 References


HEERAMA, E.P. 1979. Relations between wall friction, displacement, velocity and horizontal stress in clay and in sand, for pile drivability analysis, Ground engineering.