Effect of L/D Ratio on Degradation of Capacity of Pile Subjected to Lateral Cyclic Load in Clay

S. Basak
Lecturer, Department of Applied Mechanics, Bengal Engineering & Science University, Shibpur, Howrah–711 103, India.
E-mail: basackdrs@hotmail.com

ABSTRACT: The environment prevalent in oceans necessitates the piles supporting offshore structures to be designed against lateral cyclic loading initiated by wave action. Such quasi-static load reversal induces deterioration in the strength and stiffness of the soil-pile system, introducing progressive reduction in the bearing capacity associated with increased settlement of the pile foundation. To understand the effect of lateral cyclic load on axial response of single piles in soft clay, a numerical model was previously developed and validated by the author. Using the methodology, further analysis has been carried out to investigate how the variation in relative pile-soil stiffness and eccentricity effects the degradation of axial pile capacity due to the effect of lateral cyclic load. This paper presents a brief description of the methodology, analysis and interpretations of the theoretical results obtained from the further analysis and the relevant conclusions drawn there from.

1. INTRODUCTION

Offshore structures are usually supported on pile foundations. Apart from usual loads from superstructures, these piles are under continuous action of wave loading. This type of lateral loading is quasi-static cyclic in nature resulting in considerable degradation in the interactive performance of the pile-soil system initiating progressive reduction in pile capacity associated with increased pile-soil stiffness.

A brief review of these works indicates that this degradation under lateral cyclic loading mainly depends upon the following parameters: number of cycles, frequency, cyclic load amplitude (in case of load-controlled mode) or displacement amplitude (in case of displacement-controlled mode). As pointed out by Poulos (1981 & 1982), the degradation is mainly due to: (i) development of excess pore water pressure generated during cyclic loading in progress, (ii) destruction of interpartic le bond with rearrangement of soil particles surrounding the pile surface, and (iii) gradual accumulation of irrecoverable plastic strain around pile.

To study the degradation of soil pile interactive performance under lateral cyclic loading, a theoretical methodology based on finite difference technique has been developed. Based on this, a detailed study of single, vertical pile embedded in cohesive soil, experiencing two-way symmetrical lateral cyclic loading is done.

2. MATHEMATICAL ANALYSIS

The theoretical investigation that is reported here was aimed at developing a theoretical methodology for analyzing the effect of lateral cyclic loading on axial post-cyclic response of single pile in clay. Initially, analysis of a single pile under static lateral load was carried out. Further extension was made to incorporate the effect of lateral cyclic loading. The details of the methodology developed have been published elsewhere [Basack (2008)]. For computation, boundary element analysis was used.

2.1 Pile under Lateral Static Load

The single, vertical pile was idealized as a thin vertical strip having width equal to the pile diameter and negligible thickness. Lateral static load was applied at a certain height above G.L. The embedded portion of the pile is longitudinally discretized into a finite number of elements. Any pile element was subjected to a lateral soil pressure which was assumed to act uniformly over the surface of the entire element. Initially, the focus was to evaluate the displacements of the soil and the pile at the central nodal points of each element and to apply a condition of displacement compatibility.

The soil displacements were obtained by integrating the equation of Mindlin (1936) over each element. The pile nodal displacements, on the other hand, were evaluated by expressing the standard fourth order differential equation of an elastic beam in finite difference form. Considering the condition of displacement compatibility, together with the two more expressions regarding the horizontal load and moment equilibrium, the elastic soil pressures were obtained which were then compared with a specific yield pressure so as to incorporate local yield of the surrounding soil. The yield criterion was adopted following Brom’s (1964a) approach.
Once the soil pressures were correctly evaluated, the nodal displacements, shear force and bending moments could be easily determined. To evaluate the ultimate lateral capacity of pile, the applied lateral load was increased in small steps. The load corresponding to which all the pile elements fail or the maximum nodal bending moment or shear force exceeds the yield values for the pile in particular, whichever is less, had been chosen to be the ultimate static lateral capacity of the pile.

### 2.2 Pile under Lateral Cyclic Load

The cyclic response of the pile in clay is governed by two significant phenomena: (i) Degradation of ultimate lateral pressure and Young’s modulus of soil at the nodal points and the effect of the loading rate. (ii) Shakedown effect induced by the gradual accumulation of irrecoverable plastic deformation developed in the soil at the interface as reflected as development of soil-pile gap.

The degradation of soil strength and stiffness was quantified by a term soil degradation factor $D_{soil}$ considering recommendations of Idriss et al. (1978) and Vucetic et al. (1988). This was coupled with the effect of strain rate, as per Poulos (1982). While calculating the axial post-cyclic pile capacity, the effect of shakedown was incorporated. Starting from the uppermost soil element, a soil-pile gap was supposed to be developed for those elements, where yielding took place. However, the depth of this separation cannot be extended beyond the free standing height of the clay bed ($= 2 \frac{c_u}{\gamma}$). A composite analysis was performed in comparison to the cycle-by-cycle analysis to minimize the computational time and effort without much sacrificing the accuracy. This approximate method has been reported by other researchers to yield quite promising results. The cyclic axial capacity of the pile was calculated considering no contribution on the frictional resistance at the interface where gap has developed and the degraded values of soil strength and stiffness for the remaining portion of the interface where no soil-pile separation developed. Unless stated otherwise, henceforth in this paper, the term ‘degradation factor’ will indicate the degradation factor for axial pile capacity which was defined as the ratio of post-cyclic to pre-cyclic axial pile capacities [Basack (2008)].

The computations were carried out using a user-friendly computer software LCYC developed by the author in Fortran-77 language. The flowchart has been published elsewhere [Basack (2008)].

### 3. RESULTS AND DISCUSSIONS

The theoretical methodology and the software developed have been utilized to study the post-cyclic axial response of single prototype pile in clay. The problem is shown in Figure 1. The undrained cohesion $c_u$ of the soil has been assumed to increase linearly with depth at a rate of increment of $K_h = 3$ KN/m³, starting from a value of $c_{ud} = 30$ KPa at ground level. After the recommendations of Poulos (1971a) and Banerjee & Davies (1978), the ratio $E_s/c_u$ is reasonably chosen as 100.

![Fig. 1: (a) The Prototype Pile (b) Variation of $c_u$ with Depth](image)

The embedded length of the pile was increased sequentially such that the L/d ratio varied starting from a value of 10 up to a maximum limit of 50, incorporating gradual reduction in the relative pile-soil stiffness $K_{rc}$, the value of which has been calculated using the following relation suggested by Poulos & Davis (1980) : $K_{rc} = E_p I_p / K_h L^2$, where, $E_p I_p$ is the flexural rigidity of the pile. Analysis was carried out for the free and the fixed pile head conditions. As per Poulos & Davis (1980), pile can be considered a flexible one when $K_{rc} < 0.01$. For the present case, this happens when $L/d$ exceeds 11.54.

It has been observed from Table 1 that the values of degradation factor varied from a highest vales of 0.863 indicating less deterioration in soil-pile interactive performance to as low as 0.709 inducing remarkable loss in axial pile capacity. For identical values of cyclic loading parameters and pile geometry, the degradation of free headed pile is observed to be less in comparison with that for fixed headed pile.

It has been observed that under free head condition, the degradation factor initially decreases quite sharply with $L/d$ ratio to a certain minimum value and thereafter increases fairly linearly. The value of $L/d$ ratio at which the degradation factor attains minimum value has been observed to lie in the range of 15–25. Under fixed head condition, on the other hand, the degradation factor was observed to initially increase to a maximum value, thereafter decrease to a minimum value, and then further increases. These maximum and minimum values were found to occur at $L/d$ ratio between 15–20 and 20–30 respectively. In the initial stage when $L/d$ ratio increases, the depth of soil-pile separation is expected to increase as well up to an optimum limit. Further increment in $L/d$ ratio does not affect the depth of separation significantly but likely to increase the soil degradation factor resulting from notable reduction in the nodal strain due to reduced pile displacement at greater depth. This possible reason, coupled with head fixity in case of fixed headed pile, has initiated this peculiar pattern of variation of degradation factor with $L/d$ ratio (Fig. 2).
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Table 1: Values of Degradation Factor for Different L/d and e/d Ratios

<table>
<thead>
<tr>
<th>e/d</th>
<th>0.0</th>
<th>0.2</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
<th>5.0</th>
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<td>L/d</td>
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<td>0.829</td>
<td>0.828</td>
<td>0.827</td>
<td>0.823</td>
<td>0.817</td>
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<td></td>
<td>0.752</td>
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<td>0.809</td>
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<td></td>
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<td>0.811</td>
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<tr>
<td></td>
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<tr>
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<td>0.836</td>
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</tr>
</tbody>
</table>

* Normal font for free headed pile.
$ italicized font for fixed headed pile.

Cyclic loading parameters : No. of cycles = 1000.
Frequency = 5 cycles per minute.
Cyclic amplitude = 20%.

With alteration in e/d ratio, on the other hand, the degradation factor has been observed to decrease fairly linearly for e/d > 2 (Fig. 3). Understandably, the increment in load eccentricity induces greater moment at pile head which in turn increases the soil-pile separation as well as soil degradation and thus the degradation factor reduces.

Fig. 2: Variation of Degradation Factor with L/d Ratio for Pile Head Condition (a) Free, (b) Fixed

Fig. 3: Variation of Degradation Factor with e/d Ratio

4. CONCLUSION

From the entire investigation, it has been observed that under free head condition, the degradation factor initially decreases quite sharply with L/d ratio to a certain minimum value and thereafter increases fairly linearly. The value of L/d ratio at which the degradation factor attains minimum value has been observed to theoretically lie in the range of 15–25. Under fixed head condition, the degradation factor was observed to initially increase to a maximum value, thereafter decrease to a minimum value, and then further increases. These maximum and minimum values were found to occur at L/d ratio between 15–20 and 20–30 respectively. On the other hand, with alteration in e/d ratio, the degradation factor has been observed to decrease fairly linearly for e/d > 2.

REFERENCES


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