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INFLUENCE OF L/d AND e/d RATIOS ON THE RESPONSE OF CYCLICALLY LOADED SINGLE PILE IN UNIFORM CLAY

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ABSTRACT

The environment prevalent in ocean 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 pile in soft clay, a numerical model was previously developed by the author. Using the methodology, further analysis has been carried out to investigate how the variation in relative pile-soil stiffness and eccentricity affects 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 and the relevant conclusions drawn there from.

Keywords: Amplitude; clay; cyclic load; degradation; pile; load eccentricity; relative pile-soil stiffness

1. INTRODUCTION

Offshore structures, namely, oil drilling platforms, jetties, tension leg platforms etc. are mostly supported on pile foundations. Apart from the usual super structure load (dead load, live load, etc.), these piles are subjected to continuous lateral cyclic loading resulting from ocean waves. As reported by other researchers, this type of loading induces progressive degradation of the foundation capacity associated with increased pile head displacement.

A comprehensive review of literature indicates that limited research works have been done in the related areas. The contributions made by Matlock [1], Poulos [2], Purkayastha and Dey [3], Narasimha Rao et al. [4], Dyson [5], Basak and Purkayastha [6] and Randolph [7] are worthy of note. Some of the works were theoretical while the others had been experimental (laboratory and field based investigations). As pointed out by Poulos (1982), basically the following three reasons have been identified for such degradation of strength

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and stiffness of pile-soil system : (i) Development of excess pore water pressure generated during cyclic loading in progress. (ii) General accumulation of irrecoverable plastic deformation of soil surrounding the pile surface. (iii) Rearrangement and realignment of soil particles surrounding the pile surface.

The offshore pile foundations need to be designed considering two phenomena: adequate factor of safety against ultimate failure and acceptable deflection at pile head. The factors responsible for cyclic performance of piles have been found to be : cyclic loading parameters (no. of cycles, frequency and amplitude of applied cyclic load), relative pile-soil stiffness and load eccentricity. The aim of this investigation reported herein is to develop a theoretical model to analysis and understand the effect of lateral cyclic loading on the performance of pile foundation under axial static loading.

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 static 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, [8]). For computation, boundary element analysis was used.

2.1 Pile under lateral static load

The single, vertical pile was idealized as a thin vertical. Lateral static load was applied at a certain height above G.L. The embedded portion of the pile is longitudinally discretized into 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 [9] 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.

Once the soil pressures were correctly evaluated, the nodal displacements, shear force and bending moments could be easily determined.

2.2 Pile under lateral cyclic load

The cyclic response of the pile in clay is governed by two significant phenomena: (i) Degradation of p_{iu} and E_s at the nodal points and the effect of the loading rate. (ii) Shakedown effect induced from the gradual accumulation of irrecoverable plastic deformation developed in the soil at the interface as reflected by development of soil-pile gap in the vicinity of G.L.

The degradation of soil strength and stiffness was quantified by a term soil degradation factor D_{si} considering recommendations of Idriss et al [10] and Vucetic *et al.* [11]. This was coupled with the effect of strain rate, as per Poulos [2]. While calculating the axial post-cyclic capacity of piles, 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 (= $2c_u / \gamma$). 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.

The entire computation was carried out using a user-friendly computer software LCYC developed by the author in Fortran-77 language. The flowchart has been published elsewhere [8].

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 embedded length of the pile was increased sequentially such that the L/d ratio was 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} (= E_pI_p / E_s L^4). The values of stiffness are shown in Table 1. Analysis was carried out for free headed and fixed headed pile head conditions.

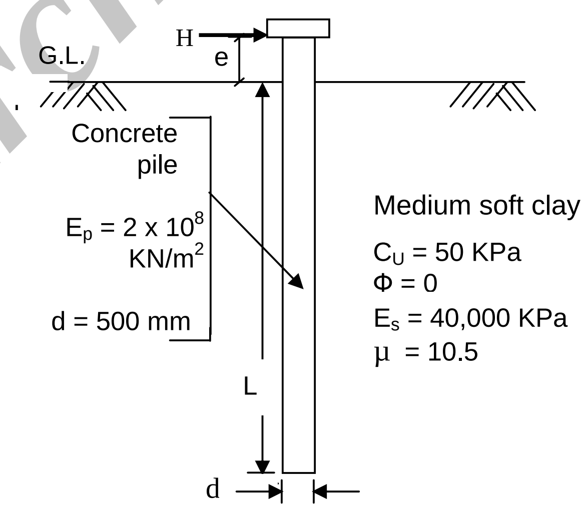

Figure 1. The prototype pile

Table 1. Values of relative pile-soil stiffness.

L/d	10	15	20	25	30	40	50
K_{rc}	0.0245	0.00485	0.001534	0.000628	0.000303	0.000096	0.000039
Critical value of K_{rc} = 0.01 at L/d = 12.52.							

3.1 Influence of cyclic loading parameters

First of all, the influence of cyclic loading parameters on the response of the pile was studied at L/d ratio of 20 and zero eccentricity. Thereafter, further analysis was done by varying the stiffness and eccentricity.

The initial static analysis has been carried out. For ascertaining the lateral static response, the method described above has been utilized, whereas in case of axial static response, the conventional method (available in any standard text book) has been followed. Analysis was carried out considering the free and the fixed pile head conditions. The lateral static ultimate capacities were evaluated as 1080KN and 1630KN under free headed and fixed headed conditions, as against the axial capacity of 746KN.

As already stated earlier, the post-cyclic soil-pile interactive response was quantified by a term degradation factor. Analysis was carried out with the following cyclic loading parameters : No. of cycles: 100, 250, 500, 750, 1000; Frequency (expressed in cycles per minute or c.p.m.): 5, 10, 15, 20, 25; Cyclic load amplitude (normalized by lateral static pile capacity): 15%, 20%, 25%, 30%, 40%.

For detailed analysis using the methodology described above, some additional parameters related to cyclic behaviour of soil apart from the soil and pile data is necessary. The values of theses parameters already considered by Basack and Purkayastha [6] have been assumed here as well.

From detailed cyclic analysis, the degradation factor was observed to vary between the maximum and the minimum values of about 0.8 to 0.2. This indicates severe loss (about 80%) of pile capacity at higher amplitudes. The author’s long experience in this field indicates that the degree of this deterioration is highly sensitive to the values of A and B to be considered for analysis.

The patterns of variation of degradation factor with cyclic loading parameters were studied carefully. The observations are sequentially described below.

Figure 2 depicts a typical plot of degradation factor versus no. of cycles. It has been observed that in almost all the cases, the degradation factor decreases with no. of cycles. Initially (upto about N=500), the reduction in value is quite considerable, but there is a tendency towards asymptotic stabilization. Understandably this is due to the fact that as per the model, the soil strength decreases exponentially with N which in addition to the effect of shakedown, has introduces this asymptotic variation.

A representative plot of degradation factor versus frequency is shown in Figure 3. For most of the cases, the degradation factor was observed to increase with frequency. Initially within 15 c.p.m., the increase is fairly pronounced after which there is an asymptotic stabilization. This type of pattern is in accordance with the consideration of logarithmic increase in soil strength with relative loading rate.

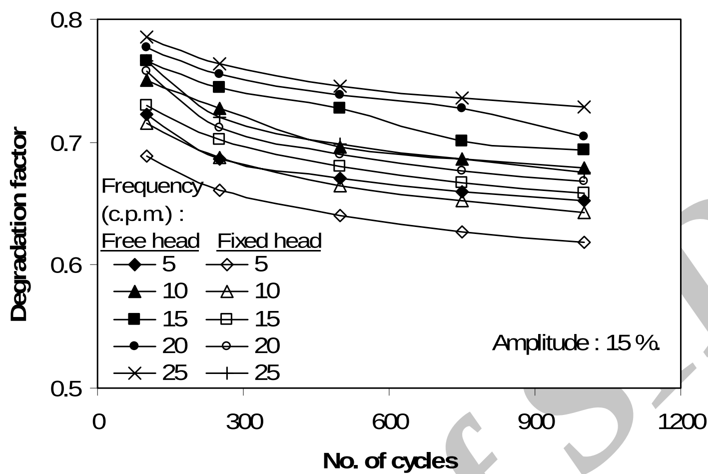

Figure 2. Variation of degradation factor with number of cycles

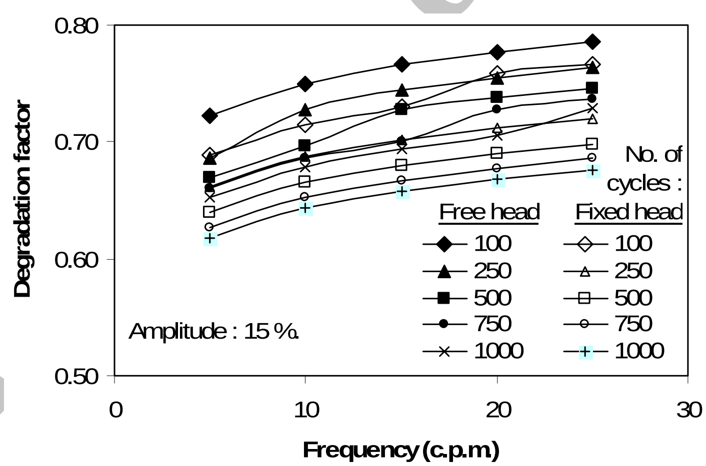

Figure 3. Variation of degradation factor with frequency

Figure 4. presents a sample variation of degradation factor with amplitude of cyclic loading. The degradation factor was observed to decrease asymptotically with amplitude. For most of the cases, the degree of reduction is quite predominant upto an amplitude of 25%. This observation is not in accordance the experimental observation of Basak (2007) where the pattern of variation was found to be parabolic; the slope of the curves being increasing sharply with advancement of amplitude.

The increase in the depth of soil pile separation with various cyclic loading parameters was studied. It was observed that although this depth is not affected by the variation in frequency, the same is affected significantly with no. of cycles and amplitude. Two typical plots, one with amplitude and the other with no. of cycles, are depicted in Figures. 5-6 respectively. The normalized depth of soil-pile separation was found to increase fairly linearly with amplitude for majority of the cyclic loading conditions, although the in some cases, the slope of these lines was observed to increase slowly with amplitude. On the other hand, this depth increases asymptotically with no. of cycles.

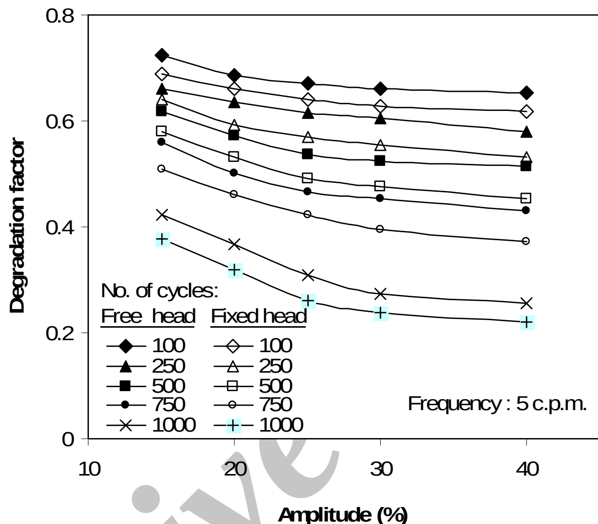

Figure 4. Variation of degradation factor with amplitude

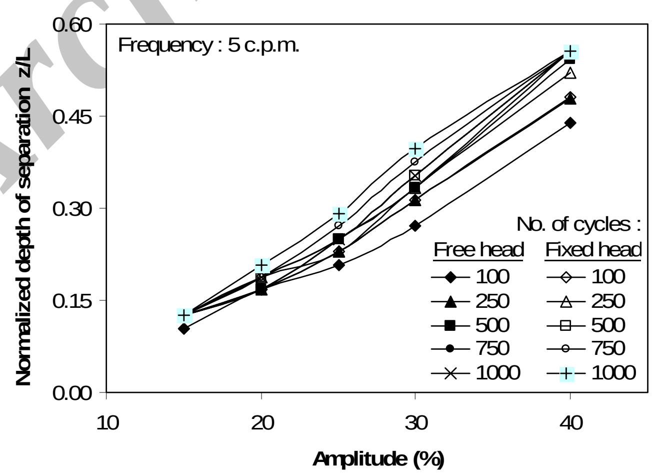

Figure 5. Variation of the depth of soil pile separation with amplitude

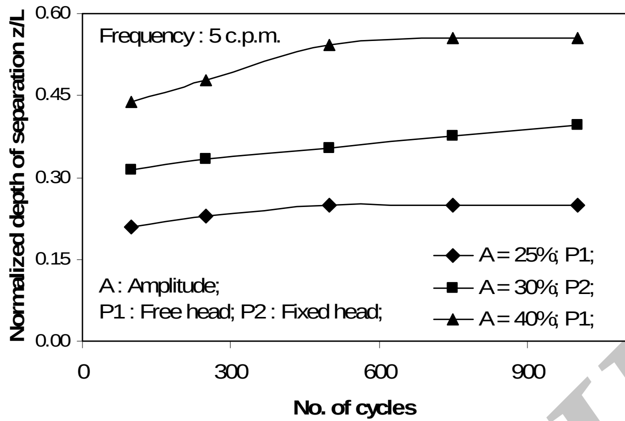

Figure 6. Variation of Variation of the depth of soil pile separation with number of cycles

3.2 Influence of stiffness and eccentricity on static lateral response

The computed values of lateral ultimate pile capacities for various L/d and e/d ratios are summarized in Table 2. The values of the ratio of static lateral ultimate capacities for fixed to free pile head conditions (referred herein as 'capacity factor') are presented in Table 3.

Table 2. Values of lateral ultimate pile capacities (N).

L/d \ e/d	0.2	0.5	1.0	2.0	5.0	10.0
10	350*	340	320	280	210	150
	930 $	*930*	*890*	*850*	*660*	*440*
15	570	560	540	500	400	300
	1130	*1110*	*1080*	*1020*	*830*	*650*
20	800	790	770	710	610	470
	1340	*1320*	*1300*	*1230*	*1090*	*900*
25	1030	1020	1000	930	740	530
	1610	*1590*	*1560*	*1520*	*1380*	*1170*
30	1120	1100	1050	980	780	550
	1900	*1880*	*1860*	*1820*	*1690*	*1280*
40	1160	1130	1080	1000	780	560
	2260	*2230*	*2160*	*2050*	*1750*	*1350*
50	1180	1150	1100	1000	790	560
	2280	*2250*	*2200*	*2090*	*1770*	*1340*

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

Table 3. Values of the capacity factors

L/d \ e/d	0.2	0.5	1.0	2.0	5.0	10.0
10	2.66	2.74	2.78	3.04	3.14	2.93
15	1.98	1.98	2.00	2.04	2.08	2.17
20	1.68	1.67	1.69	1.73	1.79	1.91
25	1.56	1.56	1.56	1.63	1.86	2.21
30	1.70	1.71	1.77	1.86	2.17	2.33
40	1.95	1.97	2.00	2.05	2.24	2.40
50	1.93	1.96	2.00	2.09	2.24	2.39

The values of lateral ultimate capacity for the free and the fixed head conditions were plotted against L/d ratio, as shown in Figures. 7-8 respectively. It was observed that for initial values of L/d ratio, the capacity increased quite sharply and fairly linearly. But whenever a certain value of L/d ratio was attained, the slope of the curves suddenly decreased. For further increase in L/d ratio, the slope of the curves gradually diminished. This critical value of L/d ratio varied in the ranges of 20-30 for free headed pile and 30-40 in case of fixed headed pile.

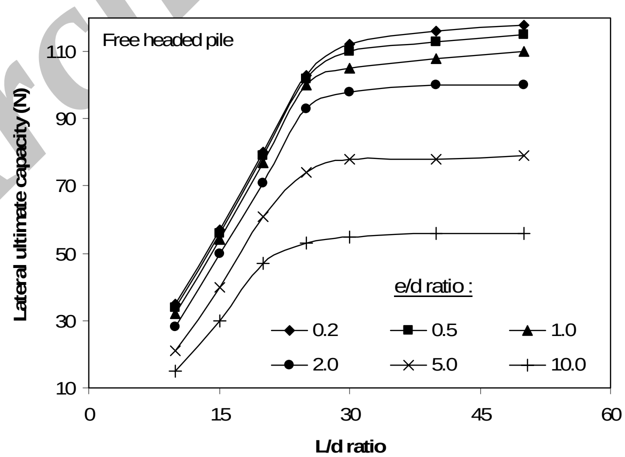

Figure 7. Variation of the lateral ultimate capacity with the L/d ratio in the case of free headed pile

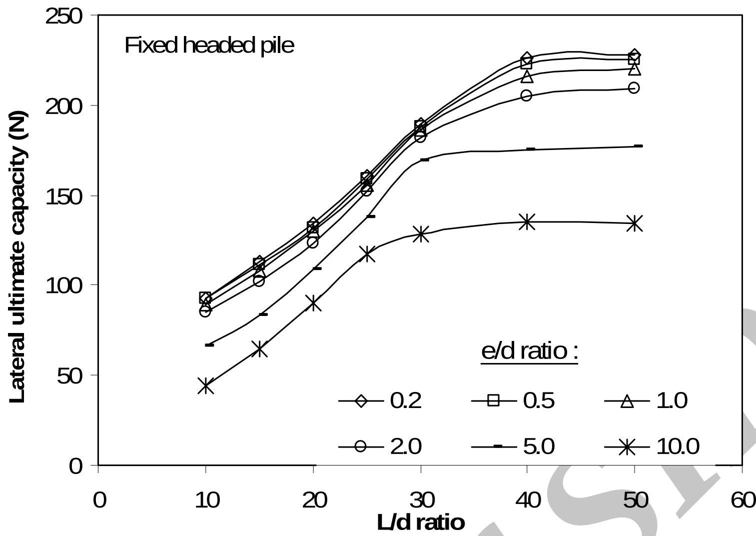

Figure 8. Variation of the lateral ultimate capacity with L/d ratio in the case of fixed headed pile

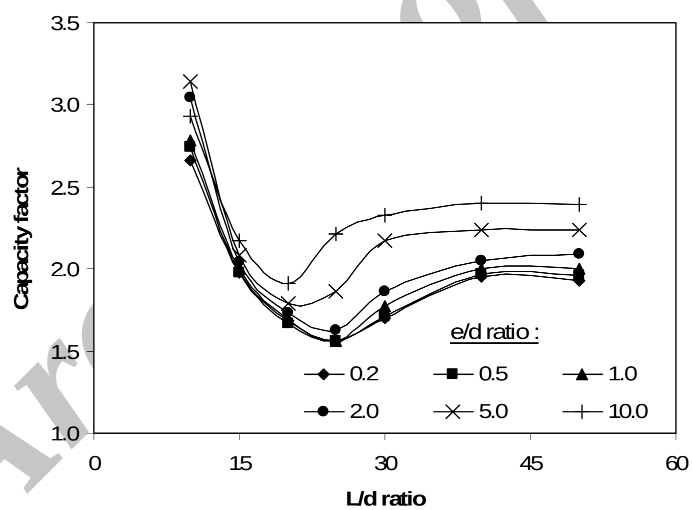

Figure 9. Variation of the capacity factor with L/d ratio

Figure 9. depicts the plot of capacity factor versus L/d ratio. Initially, the value of the capacity factor drastically dropped down with L/d ratio and reached a minimum limit. Thereafter, the curves again slopped in the upward direction and asymptotically stabilized for higher values of L/d ratio. The value of L/d ratio at which the curves attained minimum limits was observed to lie in the range of 20-25.

The values of lateral ultimate capacity for the free and the fixed head conditions were plotted against e/d ratio, as shown in Figures. 10-11 respectively. It was observed that the capacity decreased with increase in e/d ratio approximately linearly although in case of free headed pile, a tendency of asymptotic stabilization of the curves may be noted.

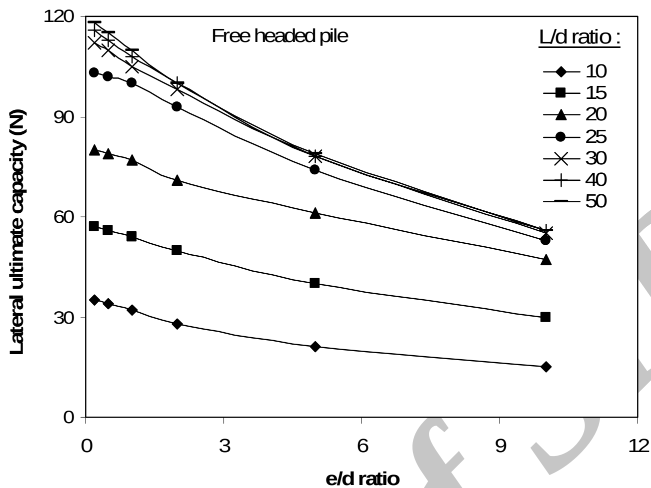

Figure 10. Variation of lateral ultimate capacity with e/d ratio in case of free headed pile

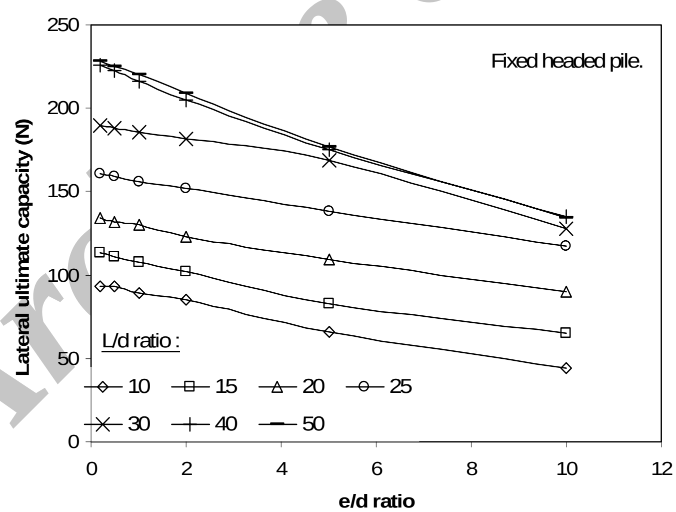

Figure 11. Variation of lateral ultimate capacity with e/d ratio in case of fixed headed pile

3.3 Influence of stiffness and eccentricity on cyclic lateral response

Analysis was carried out with the following cyclic loading parameters: No. of cycles : 1000; Frequency: 5 cycles per minute, Cyclic load amplitude (normalized by lateral static pile capacity): 20% . The values of degradation factor are given in Table 4. The degradation factors are plotted against L/d and e/d ratios, as shown in Figures. 12 and 13, respectively.

Table 4. Values of degradation factor.

L/d \ e/d	0.2	0.5	1.0	2.0	5.0	10.0
10	0.725 *	0.725	0.725	0.726	0.706	0.681
	0.600 $	*0.586*	*0.601*	*0.588*	*0.612*	*0.634*
15	0.681	0.681	0.682	0.683	0.671	0.669
	0.600	*0.600*	*0.603*	*0.605*	*0.616*	*0.623*
20	0.653	0.653	0.654	0.657	0.645	0.635
	0.594	*0.594*	*0.595*	*0.598*	*0.590*	*0.596*
25	0.629	0.614	0.614	0.619	0.632	0.646
	0.572	*0.573*	*0.560*	*0.561*	*0.565*	*0.558*
30	0.620	0.622	0.625	0.630	0.644	0.663
	0.538	*0.538*	*0.539*	*0.526*	*0.528*	*0.565*
40	0.633	0.635	0.639	0.646	0.664	0.698
	0.518	*0.519*	*0.522*	*0.526*	*0.555*	*0.579*
50	0.647	0.650	0.654	0.663	0.681	0.717
	0.544	*0.545*	*0.547*	*0.689*	*0.569*	*0.611*

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

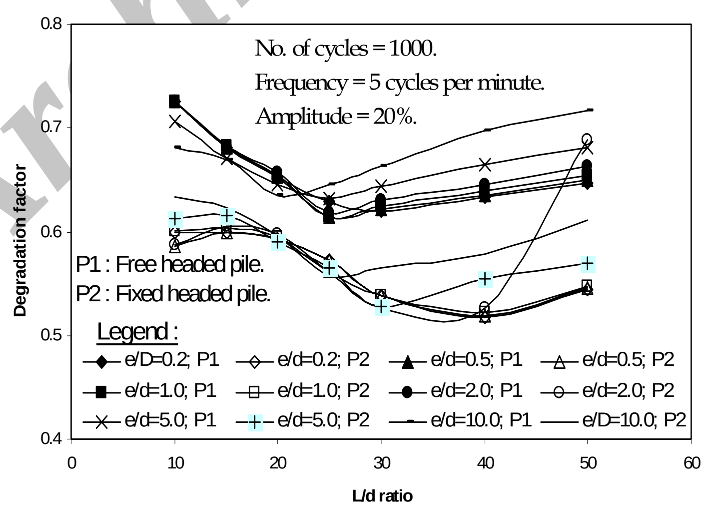

Figure 12. Variation of degradation factor with L/d ratio

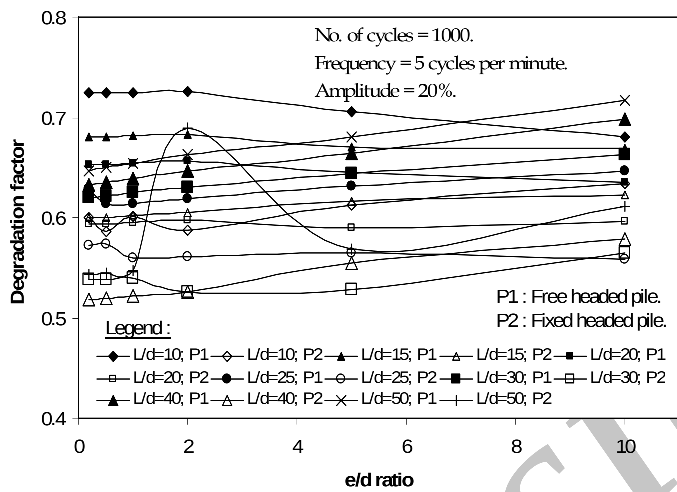

Figure 13. Variation of degradation factor with e/d ratio

It has been observed from Table-4 that the values of degradation factor varied from a highest vale of 0.725 indicating less deterioration in soil-pile interactive performance to as low as 0.518 inducing severe 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 the degradation factor initially decreases quite sharply with L/d ratio to a certain minimum value and thereafter increases rather slowly. The value of L/d ratio at which the degradation factor attains minimum value has been observed to lie in the range of 20-25 for free headed pile and 30-40 for fixed headed pile respectively.

With alteration in e/d ratio, on the other hand, the degradation factor has been observed to vary in almost curvilinear manner without any definite pattern although in few cases, the same is seen to increase fairly linearly when the e/d ratio exceeds unity.

4. CONCLUSION

Although considerable research works were carried out on cyclic lateral response of piles, investigations on the influence of relative pile-soil stiffness and load eccentricity is quite limited. From the entire investigation, the following conclusions may be drawn :

- Lateral cyclic loading introduces degrading effect on axial capacity of pile. In extreme cases, it may lead to disastrous consequences producing as high as 80% loss in capacity. The degree of such deterioration is strongly dependant upon the values of A and B parameters of the soil.
- As observed from theoretical analysis, the degradation factor decreases with no. of cycles and increases with frequency asymptotically. The degradation factor was observed to decrease asymptotically with amplitude as well.
- It was observed that although this depth was not affected by the variation in frequency,

the same was affected significantly with no. of cycles and amplitude. The normalized depth of soil-pile separation was found to increase fairly linearly with amplitude for majority of the cyclic loading conditions, although the in some cases, the slope of these lines was observed to increase slowly with amplitude.

- The depth of soil-pile separation increased asymptotically with no. of cycles.
- The lateral ultimate capacity was observed to be significantly affected by alteration in the relative pile-soil stiffness.
- It was observed that for initial values of L/d ratio, the capacity increased quite sharply and fairly linearly. But whenever a certain value of L/d ratio was attained, the slope of the curves suddenly decreased. For further increase in L/d ratio, the slope of the curves gradually diminished. This critical value of L/d ratio varied in the ranges of 20-30 for free headed pile and 30-40 in case of fixed headed pile.
- The value of the capacity factor drastically dropped down for initial values L/d ratio and reached a minimum limit. Thereafter, the curves again slopped in the upward direction and asymptotically stabilized for higher values of L/d ratio. The value of L/d ratio at which the curves attained minimum limits was observed to lie in the range of 20-25.
- The lateral ultimate capacity of the piles decreased with increase in e/d ratio approximately linearly although in case of free headed pile, a tendency of asymptotic stabilization of the curves was noted.
- The degradation factor initially decreases quite sharply with L/d ratio to a certain minimum value and thereafter increases rather slowly. The value of L/d ratio at which the degradation factor attains minimum value lie in the range of 20-25 for free headed pile and 30-40 for fixed headed pile respectively.
- With alteration in e/d ratio, the degradation factor has been observed to vary in curvilinear manner without any definite pattern. In few cases however, the degradation factor increased fairly linearly when the e/d ratio exceeds unity.

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