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The Behavior of Laterally Loaded Piles Subjected to Scour in Marine Environment

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Abstract

Pile foundations are used to transmit both vertical and horizontal loads. Many of offshore and coastal structures are founded on piles and these piles are subjected to significant amounts of lateral loads due to wind, wave and currents. Piles in shallow water regions are subjected to scour and there can be loss of soil support around these pile foundations. Bending moments and deflections are increased due to scour. In this investigation, it has been brought out that the lateral capacity of foundation is reduced due to scour. Tests on model piles of PVC and Aluminum embedded in soft marine clay bed formed at different consistency indices and load eccentricity ratios were conducted with and without scour. These pile materials are chosen such that there is a good variation in the rigidity of piles. From the model tests, it is noticed that scour results in the reduction in lateral capacity and increase in bending moments. In the second set of tests, cyclic loading is applied on PVC and Aluminum piles for a time period of 12 seconds. This time period represents the time period of storm wave in across the Indian seas. Considerable increase in deflection occurred due to scour in cyclic load tests for different consistency conditions of soil.

Keywords: *pile rigidity, consistency of the soil, load eccentricity ratio, scour depth, lateral capacity of the pile, cyclic loading*

1. Introduction

Many marine soil deposits exhibiting high compressibility and low shear strength are found along the Indian coast and in these deposits, pile foundations are usually adopted for marine structures. Pile foundations in the coastal regions are subjected to cyclic loading due to wind, wave and currents. The lateral load carrying capacity of the pile depends upon the soil and pile characteristics, load eccentricity and depth of embedment. Behavior of laterally loaded piles has been studied by several investigators. Matlock and Reese (1960) were the first few to develop design curves for predicting the deflection of piles within the range of the elastic compression of the soil. Hansen (1961) proposed a method of predicting the ultimate lateral load of rigid piles based on the theory of plasticity. Broms (1964) presented a method to determine the ultimate lateral capacity of both rigid and flexible piles assuming soil pressure distribution at failure condition. This is basically the procedure suggested by Hansen (1961) with a few modifications. Prasad and Rao (1994) carried out cyclic load tests on model steel pipe piles for cyclic load ratios of 0.30 to 0.75 and observed that the stabilized movement of pile is function of the Cyclic Load Ratio (CLR) and the number of cycles, and the movement of pile during cyclic loading is an important parameter controlling the post cyclic static behavior. Narasimha Rao and Mallikarjun Rao (1995) carried out experimental investigation on rigid piles of different diameters and consistency indices, and established a relationship between load-deflection characteristics and load eccentricities which can be used to estimate load-deflection behaviour of rigid pile at any load eccentricity.

Scour is one of the significant factors to be considered in the design of laterally loaded piles in the marine environment. Because of the formation of the scour hole around the pile, the depth of embedment of the pile reduces, and consequently there is a reduction in load carrying capacity of piles. Several investigators studied the scour depth and scour pattern around piles in cohesive and cohesionless soils. Ram Babu et al (2003) conducted wave flume studies on pile embedded in clay bed and brought out that the scour depth can be related to the soil characteristics, flow velocities and wave heights for structures located in the marine environment.

From the literature, it is found that not much work has been carried out in combination of scour with lateral loading on piles. Hence, in this investigation, model studies are carried out to explore the effect of scour on lateral pile behavior.

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2. Experimental Investigation

2.1 Soil Used

Soil used in this investigation was taken from the coastal deposits along the East Coast of India (near Chennai), which is a silty clay of medium plasticity. Various tests were conducted on this soil to determine the index properties, grain size distribution and other properties as per relevant ASTM D 422-62 (1972) and ASTM D 4318 (1984). The index properties of the soil used are,

Natural moisture content (n.m.c.)= 33%
Liquid Limit (L.L.) = 40%
Plastic Limit (P.L.) = 18%
Plasticity Index (P.I.) = 22%
The soil consists of
Clay fraction = 44%
Silt fraction = 47%
Sand fraction = 9%

2.2 Soil Bed Preparation

The soil in a fully saturation condition was carefully hand packed into the test tank in layers of 50mm thickness, holding the pile in vertical position. Each layer was pressed with wooden template so as to remove the entrapped air. Moisture content and density measurements confirmed uniformity in the soil bed formation at different depths and locations. The full saturation of soil is confirmed by the measurements of pore water pressure parameter of B = 0.98 to 0.99 (Bishop and Henkel, 1962) on specimens tested in Triaxial test assembly. The moisture contents used in this testing program were conformed to soft to medium stiff consistencies to suit all the field conditions.

2.3 Test Setup and Model Piles

The tests are conducted on steel tank of size 1000mm in diameter and 1300mm height. The diameter of test pile is 50mm. The diameter of the test tank in this study is higher than the 10 times the diameter of the test pile. In view of this, it is felt that the size effects are considered to be negligible. A similar such arrangement was made earlier in this laboratory (Mallikarjuna Rao, 1993).

The test tank was placed inside a loading frame made up of 200 mm × 75 mm ISMC structural steel sections. The lateral load was applied with the help of cast iron weights placed over the loading pan, which in turn was connected to the pile through pulley arrangement. A load cell of 2 kN capacity was connected between the loading pan and the pile so as to measure the load accurately. The load cell was periodically calibrated. The output from the load cell was measured using a carrier frequency amplifier (CFA). The lateral displacement of the pile at ground level was measured with the help of inductive type displacement transducer (e.g., LVDT).

Model pipe piles of PVC and Aluminum were used in testing and these materials were used such that there is a good variation in the rigidity of piles. Rigidity of pile is expressed in terms of Relative Stiffness Factor (K_{rc}). Relative stiffness factor, K_{rc} is defined as E_pI_p/E_sL^4, where E_s=soil modulus, E_p=Young's modulus of pile material, I_p=Moment of inertia of pile and L=embedment length of pile. Relative stiffness factor of PVC and Aluminum piles are presented in Table 1. Laterally loaded piles are treated as rigid if the value of $K_{rc}\geq 10^{-2}$ (Polous and Davis, 1980) and as flexible if the value of $K_{rc}<10^{-2}$.

These piles were instrumented with electrical resistance type of strain gauges of gauge length 5 mm and gauge factor of 2.0. These gauges were used to trace the variation in bending moments and lateral deflections with depth. Model piles of 50 mm diameter and of length 1000 mm were used in this testing.

2.4 Test Procedure

2.4.1 Static Load test

In the loading frame, a pulley arrangement was made to apply the lateral load on the pile. Loading was done in increments by using the cast iron weights and each load was maintained till the rate of deflection reached a value less than 0.02 mm/hr. The testing was continued till the deflection at the ground level reaches 20% of the pile diameter. This method was followed for all static lateral load tests on the model piles in this investigation. The experimental setup for static loading is shown in Fig. 1.

2.4.2 Cyclic Load test

A Specially designed stress-controlled pneumatic loading device was used to apply cyclic loading. The regulated air under pressure was fed to the double acting pneumatic power cylinder through solenoid valve which in turn moved a piston back and forth. An electronic timer controlled the loading frequency. The piston rod of the cylinder was connected to the load cell with suitable coupling while the other end of the load cell was connected with an extension rod such that it could transfer the load on to the pile. Groundline deflections were measured by

Table 1. Relative Stiffness Factor (K_{rc}) Values

S. No.	Pile Material	Flexural Rigidity EpIp ($N\text{-}mm^2$)	Consistency Index of Soil (I_c)	Soil Modulus Es (KPa)	Relative Stiffness Factor K_{rc}
1	Aluminum	6.50×10^9 6.50×10^9 6.50×10^9	0.32 0.48 0.60	870 1470 1950	0.0074 0.0044 0.0033
2	PVC	2.63×10^5 2.63×10^5 2.63×10^5	0.32 0.48 0.60	870 1470 1950	3.02×10^{-7} 1.78×10^{-7} 1.34×10^{-7}

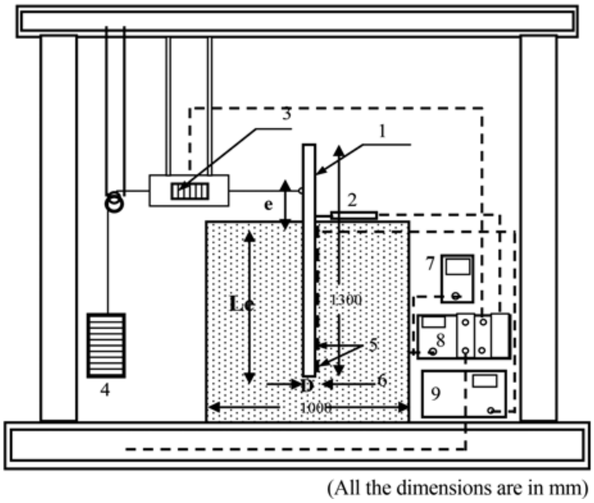

Fig. 1. Schematic Diagram of Experimental Setup for Static Loading, 1. Model pile, 2. LVDT, 3. Load Cell, 4. Load Hanger with Applied Loads, 5. Strain Gauge, 6 Soil Bed, 7. Multimeter, 8. Carrier Frequency Amplifier (CFA) 9. Data Logger

using a LVDT. Cyclic loading was applied in cyclic load ratios of 0.5, 0.6, 0.7 and 0.8 (Cyclic Load Ratio=applied cyclic load/ultimate static load). The experimental setup for cyclic loading is shown in Fig. 2.

2.4.3 Preformed Scour Holes

The scour hole formed should have some relevance to field values. In a recent study by Ram Babu (2003), an effort had been made to compile the scour depths observed in marine work and an elaborate testing programme involving scour studies on piles subjected to waves and current action was carried out. The studies brought out that the maximum scour in cohesive soils can be 0.7 to 1.0 D (D = diameter of pile).

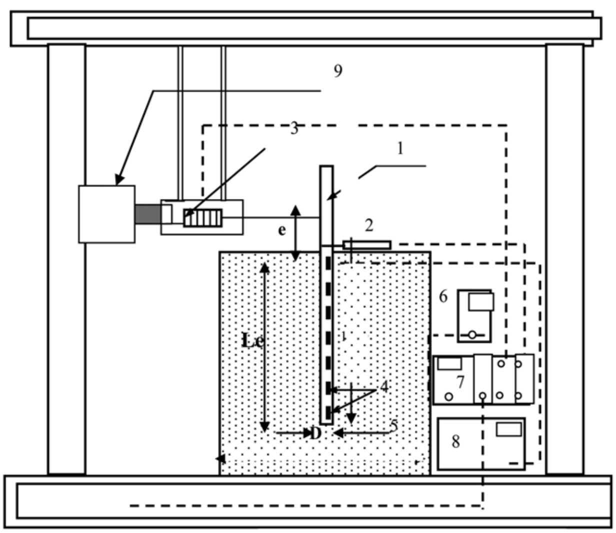

Fig. 2. Schematic Diagram of Experimental Setup for Static Loading, 1. Model Pile, 2. LVDT, 3. Load Cell, 4. Strain Gauges, 5. Soil Bed, 6. Multimeter, 7. Carrier Frequency Amplifier (CFA), 8. Data Logger, 9. Pneumatic Cylinder

2.5 Variables of the Testing Program

Based on the above considerations, the testing programme has been carried out as per the following schedule.

Table 2. Variables of the Testing Program

S. No.	Parameters of the model studies	Description/values
1.	Model piles	PVC and Aluminum
2.	Load eccentricity ratio (e/D)	3,4 and 5
3.	Consistency of the soil (I_c)	0.32, 0.48 and 0.60
4.	Type of the loading	Static and cyclic loading
5.	Scour depth ratio (S_u/D)	1.0

Schematic diagram representing parameters of experimental program is shown in Fig. 3.

Consistency Index of soil can be defined by I_c=LL-WC/PI, where LL= liquid limit; PL=plastic limit; WC=water content and PI=plasticity index.

3. Results and Discussion

3.1 Static Load Analysis

3.1.1 Load vs Groundline Deflection Curves

Lateral capacity has to be obtained from corresponding to a certain level of deflection from load-deflection curves. The ultimate lateral capacity can be taken as the load that causes certain amount of deflection, which is equal to 0.2D (Broms, 1964). A typical set of load-deflection curves without scour as obtained from tests on PVC pile and Aluminum piles at three values of load eccentricities at consistency index, I_c of 0.32 is presented in Fig. 4. From the figure, it is observed that the load corresponding to groundline deflection of 10 mm for PVC pile at e/D (e=load eccentricity and D=diameter of pile) of 3 is 120 N and that of Aluminum pile is 400 N and at the load eccentricity of e/D=5, ultimate lateral capacity of PVC and Aluminum piles are 125 N and 295 N, respectively. It is clear that Aluminum piles show higher lateral capacity compared with that of PVC

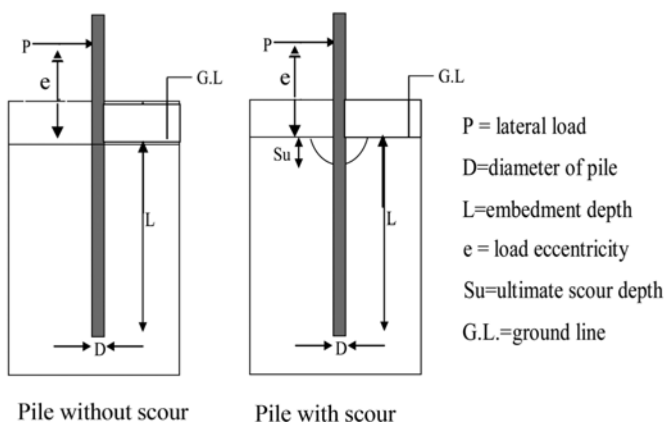

Fig. 3. Schematic Diagram of Parameters of Experimental Investigation

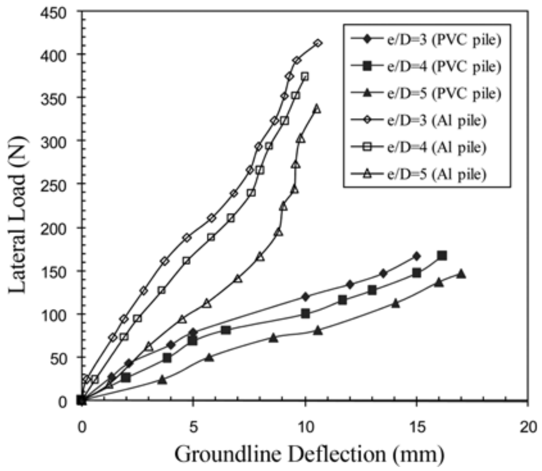

Fig. 4. Load vs Groundline Deflection of PVC and Aluminum Pile

piles. For all the consistencies of soil, Aluminum pile behaves like rigid pile and where as PVC pile like flexible pile. From above discussion it is found that lateral capacity is a function of rigidity factor.

3.1.1.1 Influence of Scour

Typical Load –deflection curves for the piles with and without scour are presented in Fig. 5. The load-deflection curves in respect of the piles without scour are presented in full solid lines where the results obtained with pre-formed scour holes are presented in dotted lines. From the figure, the ultimate lateral capacity of PVC pile at e/D of 3, 4 and 5 (without scour) is observed as 120 N, 100 N and 78N, respectively and values of ultimate lateral capacities for the same load eccentricity ratios of preformed scour are 117 N, 86 N and 65 N respectively. The reduction in the capacity of the PVC pile with scour is in the order of 18% and in case Aluminum pile is 15%. This reduction is mainly due to loss of the soil support and loosening of the soil around the pile.

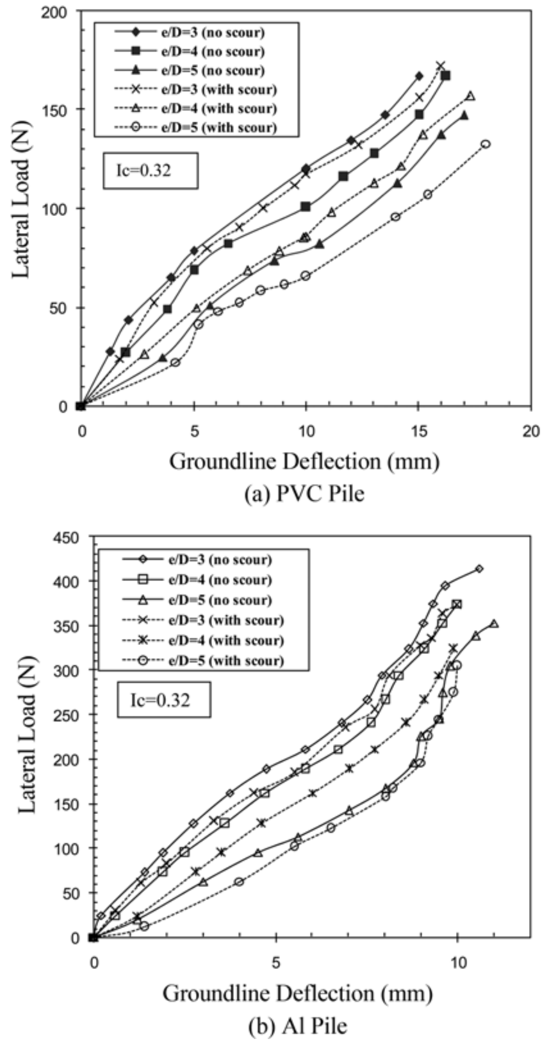

Fig. 5. Lateral Load vs Groundline Deflection for Different Eccentricity Ratios at I_c=0.32

3.1.2 Influence of Load Eccentricity

In most of the offshore piles, the load is applied above the mud line and this induces additional moments. Hence, this height of load application is applied at each consistency in terms of e/D ratio. The height of load application has been varied from 150 mm to 250 mm on all the test piles. From Fig. 6, it is observed that at I_c=0.32, the ultimate lateral capacity of PVC pile without scour for e/D of 3 is 120 N and for e/D of 5 is 78 N. Similar trend is observed for all consistency of the soil. As the e/D is increased 3 to 5, the percentage reduction in capacities is observed as 33% for Aluminum pile and 35% for PVC pile. This shows significant reduction in the lateral load carrying capacity of the pile with an increase in load eccentricity. The increase in the load eccentricity induces additional lateral thrust on the soil and this results in increased values of moments and deflection and hence there is a reduction in the lateral resistance of pile.

3.1.3 Bending Moment Variation Along the Depth

Bending moments are computed based on the measurements carried out through the electrical strain gauges fixed along the length of the pile. From these bending moments, lateral deflections along the length of pile are calculated for different consistencies of soil, load eccentricity ratios and cyclic load ratios. Typical variations in bending moment with depth for static loading at consistency index, I_c of 0.32 for PVC and Aluminum piles for with and without scour are shown in Fig. 7. It is observed that, for PVC pile, bending moments are increased upto a depth equal to 6 D (D=diameter of the pile) and beyond which the moment is reduced reaching even zero value. It is noted that the maximum bending moment occurs at a depth equal to 6 times diameter of pile and the first point of zero moment (point of inflection) occurs at a depth equal to 10 to 11 times the pile diameter. The reversal of bending moment is also seen in PVC piles, indicating rotation and severe bending. In case of Aluminum piles, bending moments with depth increase upto 4 to 8 D depth below groundline and beyond which bending moment drops down even reaching zero at the base of the pile. The point of contra flexure occurs in between 12 to 18 D.

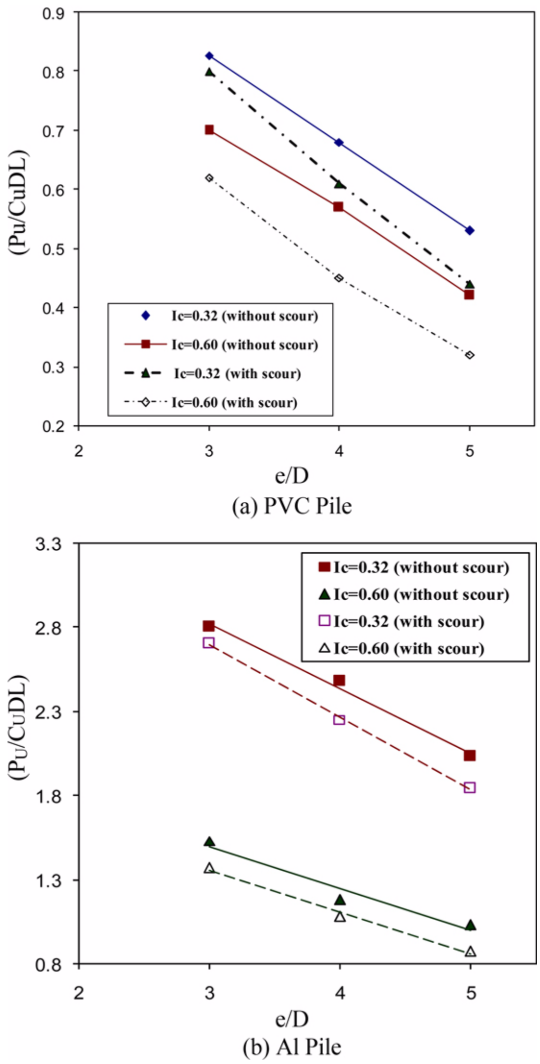

Fig. 6. Variation of Ultimate Lateral Capacity with Eccentricity for Different Consistency Indices

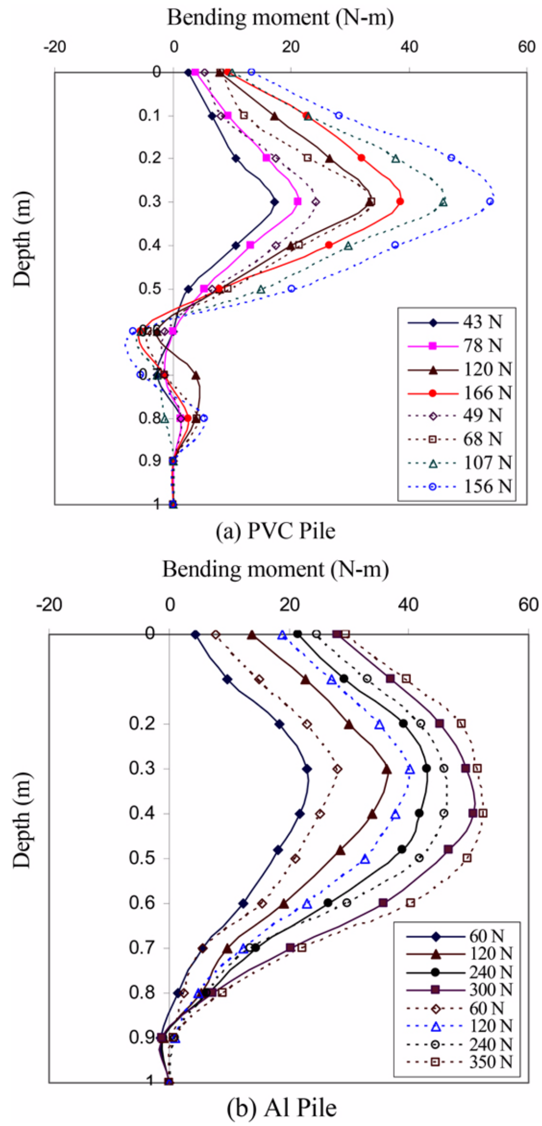

Fig. 7. Variation of Bending Moment with Depth for PVC Pile at Ic =0.32 and e/D=3

The results obtained from tests on piles with and without scour depths are shown in Fig. 7. Bending moments without scour represents in solid lines and with scour in dotted lines. Similar trends are noticed in these tests on piles with scour. Variation in the bending moment with and without scour is the order of 20 % for PVC pile and 17% for Aluminum pile.

3.2 Cyclic Load Analysis

3.2.1 Influence of Cyclic Load Ratio

Cyclic lateral load tests are conducted on model piles embedded in clay bed formed at consistency index, I_C of 0.32, 0.48 and 0.60 and these loads are applied at load eccentricity ratio, e/D of 3, 4 and 5 for piles at embedment depth ratio, L/D of 20. All these tests are conducted for both with and without scour. The typical variation of groundline deflection with number of cycles at different cyclic load ratios is shown in Fig. 8. From all these results, it can be seen that as the number of cycles increases, ground level deflections increase up to a certain number of cycles and thereafter, they get stabilized. At the initial stage, there is almost a linear increase in deflection with the number of cycles at all the three consistencies and for the tests conducted at all e/D values. Beyond this range, there is a curvilinear pattern of variation. With a further increase in load cycles, there is not much increase in the deflections and the curve between deflections and the number of cycles is almost asymptotic to the X-axis. In all these cases, this increasing trend in deflection is seen up to about 300 cycles and beyond it, the deflection is almost constant. It can also be observed that the cyclic load level has a significant influence on the deflections. As the cyclic load ratio increases from 0.5 to 0.8, the ground level deflections are on the increase and there is approximately 2 to 5 fold increase in the deflection level.

The typical variation of groundline deflection with the number

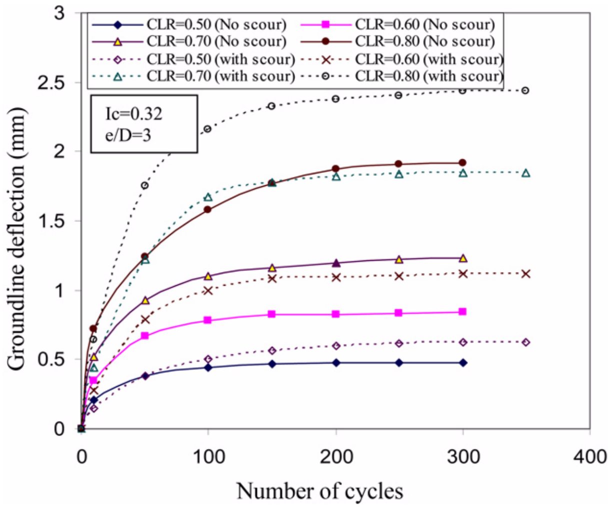

Fig. 8. Variation of Groundline Deflection with Number of Cycles for Different Cyclic Load Ratios

of cycles with and without scour is shown in Fig. 8. It is observed that for all the Cyclic Load Ratios (CLR), there is a considerable increase in groundline deflections with scour compared to that of without scour. The variation in groundline deflection with scour is very high for lower CLRs and at the higher CLRs (0.8) this variation is in the order of 14% for PVC pile and 21% for aluminum pile.

4. Conclusions

Based on this investigation, following conclusions are drawn.

1. With the formation of scour, reduction in the ultimate lateral capacity is in the order of 18% for PVC (flexible) pile and 15% for Aluminum (rigid) pile.
2. At all the consistencies of the soil, reduction in the ultimate capacity of pile with increase in load eccentricity ratio (3 to 5) is in the order of 30%.
3. Based on the bending moment of pile computed from strain gauges, it is found that increase in the bending moment with scour compared with that of without scour is in the order of 17%.
4. When the pile is subjected to cyclic loading, an increase in groundline deflection with scour is two to five folds compared with that of without scour.

Nomenclature

CLR : Cyclic Load Ratio
Cu : Undrained shear strength
D : Diamater of pile
d : Water depth
e : Load eccentricity
f : Submergence depth
Ic : Consistency Index
Krc : Relative stiffness factor
L : Embedment length of pile
Pu : Ultimate lateral load
Su : Ultimate scour depth

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