Nonlinear Analysis of Laterally Loaded Pile Group in Layered Soil-Ash Deposit

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Abstract. The current scenario for the geotechnical engineering is not only to take care of vertical load of super-structure impending to the soil but also the lateral load subjected to the structure must be taken into consideration for the safe design of foundation. For designing pile foundation, knowledge of load-deflection behavior of pile under moderate to heavy load is necessary. In the present study, numerical analysis of pile group in a layered soil-ash system has been performed using SoilWorks software. The analysis is based on P-Y curve method which is a realistic and practical method for the load deflection analysis of pile under lateral loads. The pile arranged in grid form in 3x3 and 4x4 pattern. The influence of pile diameter effects along with various pile spacing on the behavior of the pile-soil system has also been studied. The stability of pile was checked under horizontal and vertical condition. The pile group has been analyzed with vertical load, lateral load and moment at the top end of the pile. The response of the pile includes horizontal displacement, shear force, moment and ground reaction along the pile length.

Keywords: P-Y curve, Lateral load, Pile group, Layered soil-ash system

1 Introduction

Pile foundations are the muse consisting of range of piles connected with a pile cap to transmit structural load from low bearing capacity layer to onerous strata. It is not solely made to take care of axial load however conjointly the lateral loads. Lateral loads are quite common to the structures like tall building, transmission towers, offshore platforms, wharfs and jetties, bridge abutment wall and it is because of the result of wind action, wave action, traffic load, earthquake, lateral pressure, ground movement and impact load from ships. Therefore, a proper understanding of response of pile under lateral loading includes a nice importance in analysis and design of piles. There are many approaches/methods are available for the analysis of behavior of laterally loaded piles. Based on theory of elasticity, an elastic solution of single pile subjected with lateral load was given by Poulos [10] and it assumed the soil is homogenous, isotropic, elastic which is not the practical situation. This theory gives more accurate results for the soil which is linearly elastic in nature but soil is nonlinear in nature. According to theory of subgrade reaction, a method was presented by Broms [1] for computing moment and lateral deflection of pile under drained situation in the case of cohesive soil. The advantage of this method is that it can be applicable for pile with free-headed or perfectly fixed whereas it is applicable only in working load range. The past methods assumes the subgrade modulus is linearly varing with depth [2]. The concept of “p-y” curve was first introduced by McClelland and Focht [8] and it was used to find the subgrade modulus along the depth. The p-y method is simple and quite realistic because of it assumptions and semi-analytical approach. Different researchers used the p-y curve with separate assumptions considering the different types of soils, like medium stiff clay, submerged soft clay, submerged stiff clay, sand, unified clay [3, 7, 11 and 12]. Based on the results of past study the p-y curve majorly contains nonlinear steep incremental parts and flat linear part when it reaches a certain level of pressure. After p-y method, Brown [4] developed a method called p-multiplier method, in this method the p-y curve of single pile are multiplied by a constant for the lateral response of pile.

The laterally loaded pile was investigated using finite element techniques by several researchers [6, 9 and 13]. The FEM softwares used for the study include ABAQUS, OASYS Alp 19.2, FLPIER etc. To perform the analysis the pile was considered as linear elastic beam with different models like Mohr-Coulomb, Drucker-Prager and Modified Drucker-Prager model.

The findings of the present study focus mainly on the capacity of laterally loaded pile with stratified soil deposits. The analysis of stratified soil system is done using SoilWorks software using the concept of P-Y analysis. Here, the influence of length, diameter, arrangement and pile cap dimension has been considered for lateral behavior of piles. The results of the pile response are presented in the form of horizontal displacement, ground reaction, shear force and bending moment along the pile length.

2 Overview of SoilWorks

SoilWorks is a finite element software which has major application in Geotechnical as well as Structural Engineering field. It is made especially for the analysis and design for tunnel, slopes, foundation, seepage, excavation cases under normal and seismic conditions. Using SoilWorks the modeling of any types of structure can be done easily and also it can import Auto-CAD files directly. SoilWorks also has one specific module dedicated to analysis of foundation. Here, the analysis of laterally loaded pile group in layered soil-ash deposit has been performed based on P-Y analysis. The horizontal stability of foundation is checked by P-Y analysis and it considered the allowable displacement limited to 1% of pile diameter. The soil was represented by means of a series of non-linear P-Y curves that changes in magnitude with depth and soil type. The layered soil system consists of three layers namely fly ash, alluvial layer and weathered soil. In the present study, the pile of length-12m and 14m and diameter–1.0m and 0.5m has been considered for the analysis. Fig. 1. represents the schematic figure of soil-pile interaction model with stratified soil system.

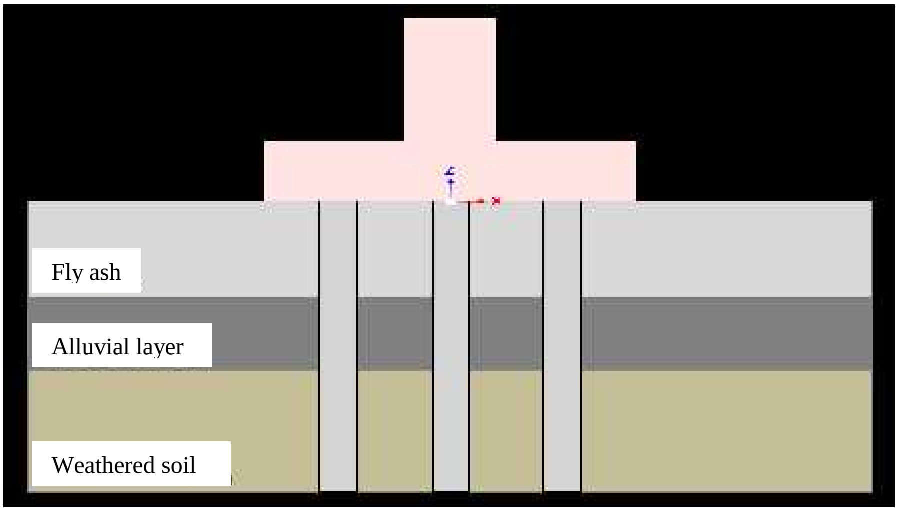

Fig. 1. Typical representation of piles with layered soil system

3 Materials Used

The material used in the present study is made up of concrete having modulus of elasticity $2.5x10^7$ kN/m^2 and Poisson's ratio of 0.18. The layering of soil was done by placing fly ash as top layer followed by alluvial layer and then weathered soil with depth of 4m, 7m and 12m respectively. The lateral load applied at the top level of pile taken from the load-deformation plot by fixing the load corresponding to 10mm deformation. In this case pile capacity is calculated considering both the skin friction and end bearing. Table 1. depicts the material properties of soil which was used in analysis of laterally loaded pile.

Table 1. Properties of layered soils used for the present study

Name	Fly ash	Alluvial layer	Weathered soil
Model Type	Silty	Sand	Sand
Unit Weight (kN/m^3)	15.89	16	17
Saturated Unit Weight (kN/m^3)	16.866	18	19
Cohesion (kN/m^2)	45.45	-	-
Angle of Internal Friction (°)	31	25	26
Material Type	Silt	Sandy Soil (API)	Sandy Soil
Horizontal Reaction (kN/m^3)	30000	-	16000
Unit Ultimate Skin Friction (kN/m^2)	31.82	20	30
Unit Ultimate Bearing Capacity (kN/m^2)	440	600	4000

4 Load-Deflection Response

The representation of pile response when subjected to lateral load with deflection of pile head has been plotted considering variation in pile geometry. The load-deflection response of laterally loaded pile is nonlinear in nature most of the time. Because of this nonlinearity there is no well-defined peak point to determine ultimate load. Therefore, the lateral load corresponding to 10mm of deflection can be taken as ultimate lateral load for each case. Fig. 2. shows the load-deflection plot for different L/D ratio. Similarly, lateral load determined at 10mm of deflection has shown in Table 2.

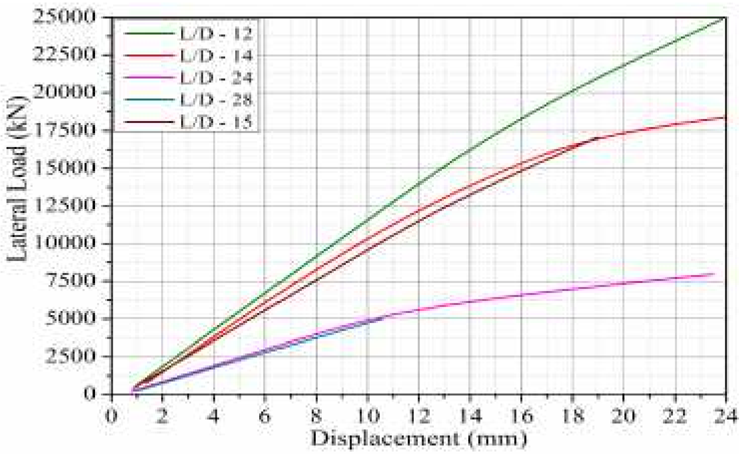

Fig. 2. Load-Deflection curves for different L/D ratio.

Table 2. Lateral load capacity corresponding to 10mm deflection

S.N	Case	Pile Parameters (m)	Lateral Load (kN)
1.	Case-1	L = 12 & D = 1.0	11650
2.	Case-2	L = 12 & D = 0.5	5000
3.	Case-3	L = 14 & D = 1.0	10400
4.	Case-4	L = 14 & D = 0.5	4750
5.	Case-5	L = 12 & D = 0.8	9500

5 P-Y Analysis

The P-Y investigation helps in correlating soil resistance with deflection and soil is configured as nonlinear springs. In this analysis ‘P’ represents the soil pressure per unit length of the pile and ‘Y’ is the pile deflection. The lateral deflection of pile decreases the carrying capacity of pile and surrounding soil. At small deflection the soil behaves as stiffer material, similarly the stiffness of pile decreases with increase in applied moment. Since numerical analysis is involved, therefore it can be used to analyses soil with varying depth and variation in pile configuration. The P-Y analysis gives results in good agreement with field loading test and also with several available approaches like characteristics load method (CML) [5]. Fig. 3. represents the typical plots of P-Y curve of single pile at different depths. The slope of P-Y curve represents the tangent soil stiffness at any deflection. From Fig. 3, it can be seen that for lower depth the P-Y curve is linear in nature and peaks can be identified easily whereas for higher depth the P-Y curve changes from linear to non-linear. And also the soil resistance is increasing with increase in depth of soil. The soil resistance depends on stiffness of the spring in P-Y analysis.

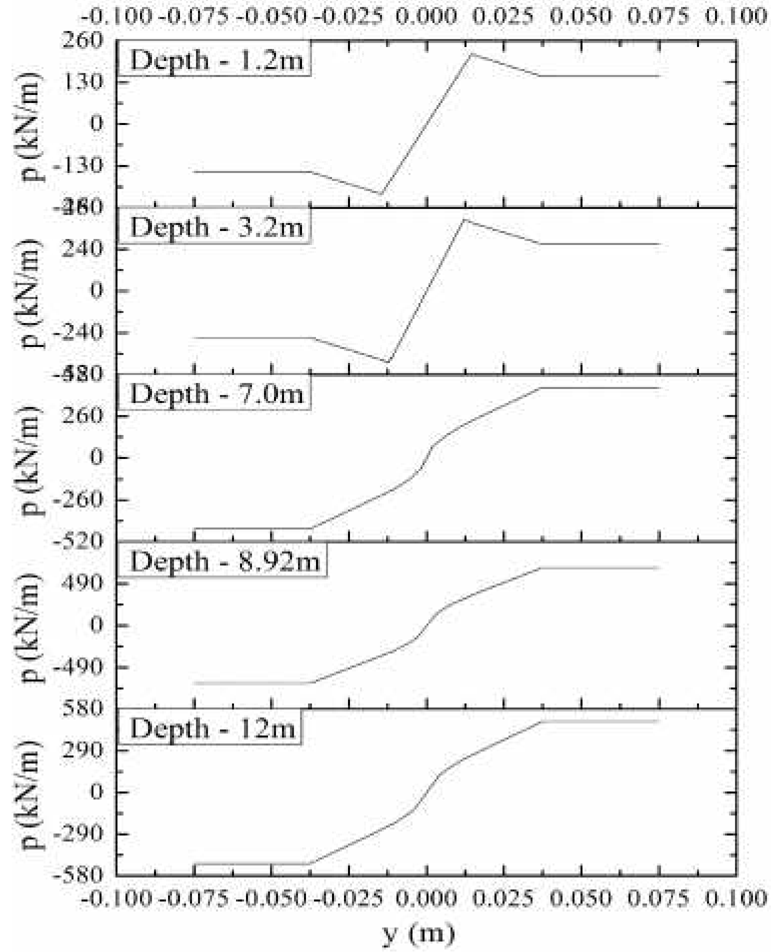

Fig. 3. P-Y Curves for single pile (L-12m and D-1.0m)

6 Response of Pile Subjected to Lateral Load

For the determination of pile response, first of all the ultimate load that the pile can take was determined using the IS 2911-P-3 (2010) method. The load consists of both skin friction and end bearing under different length and diameter of pile. After determination of load, the load-deflection curve was plotted so that the lateral load can be found out. The lateral load was the load corresponding to the deflection of 10 mm. Also the variation in pile response according to the change in arrangement [4x3, 5x3, 6x3, and 7x3 in which L: 13m, 16m, 19m, 22m & B: 10m respectively] has been studied. The results of pile response have been discussed in the following sections.

6.1 Horizontal Displacement

In the present study the horizontal displacement is the lateral displacement caused due to lateral load of 11650 kN, vertical load of 31088.16 kN and moment of 7772.04 kN-m. The displacement response of pile has been represented in terms of variation in length and diameter and arrangements of piles. The contribution of change in length of pile for displacement was very less as compared to change in diameter. This may be because of the variation of length influences the surface resistance only whereas diameter influences both surface as well as base resistance of pile. The plots of different L/D, diameter and arrangements are presented in Fig. 4, Fig. 5 and Fig. 6 respectively. From Fig. 4, the horizontal displacement is found to be maximum at the top of the pile and decreases as the depth increases, because the soil resistance increases with depth. In the same way horizontal displacement is increasing with decrease in pile diameter, this occurs due to the decrease in surface area of pile which is represented in Fig. 5. In Fig.6. it is clearly shown that when the pile cap size is increasing the horizontal displacement decreasing and also shadowing & edge effect is more in higher pile number arrangement.

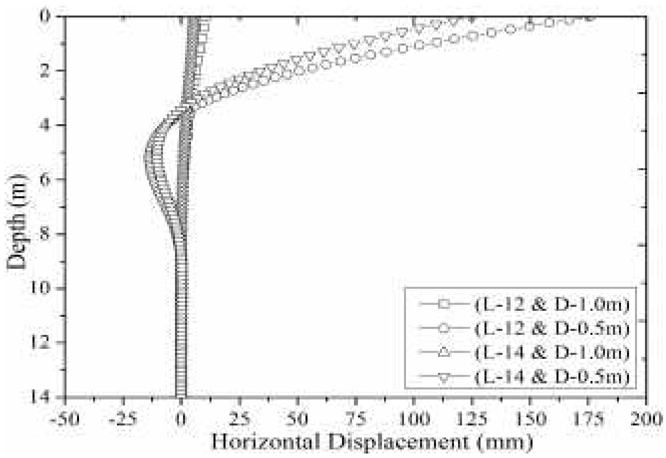

Fig. 4. Typical plot of Horizontal Displacement with depth for different L/D ratio (Arrangement - 7x3)

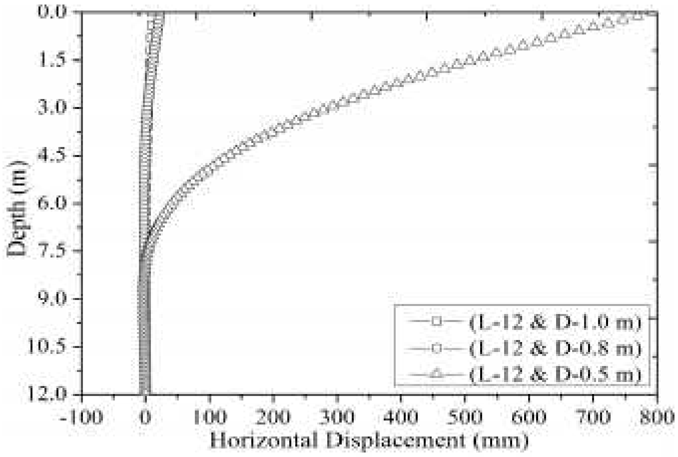

Fig. 5. Typical plot of Horizontal Displacement with depth for different diameter (Arrangement – 4x3)

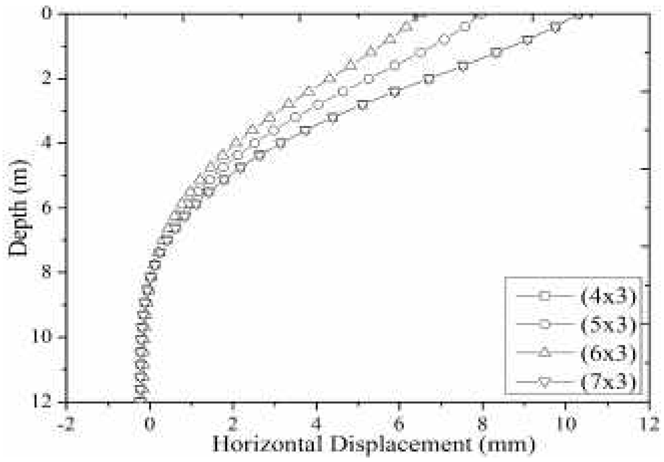

Fig. 6. Typical plot of Horizontal Displacement with depth for different arrangements (L-12m & D-1.0m)

6.2 Ground Reaction

Ground reaction is also known as soil resistance, which is developed when pile subjected to lateral load/movement. In this case also the pile was subjected to lateral load, vertical load and moment of magnitude 11650 kN, 31088.16 kN and 7772.04 kN-m respectively. The ground reaction was plotted by taking into consideration of L/D effect and change in arrangement of piles. It is increasing with increase in L/D and also it shows sharp increase in reaction when the density of soil changes. With increase in number of piles, ground reaction increases upto certain limit and then decreases. The plot of different L/D and arrangements are shown in Fig. 7. and Fig. 8.

respectively. Fig. 7. shows much variation in ground reaction for smaller diameter of pile than that of larger diameter and there is a sharp change in ground reaction as the density changes. Fig. 8. shows that the ground reaction is maximum below the ground surface and it can be identified upto certain depth after that the all arrangements merge one over the other.

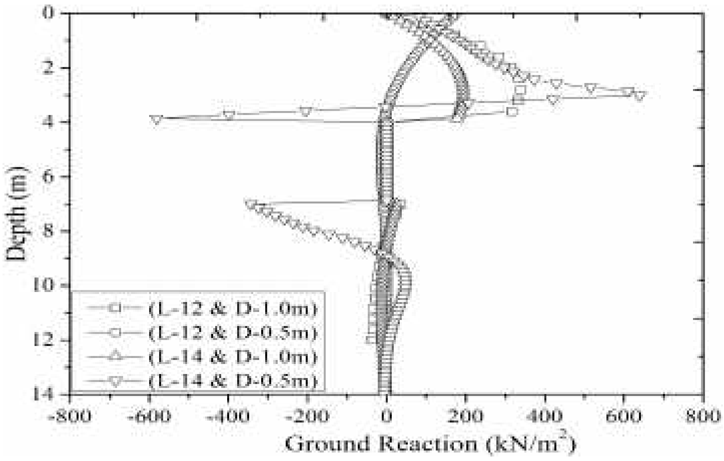

Fig. 7. Typical plot of Ground Reaction with depth for different L/D ratio (Arrangement – 7x3)

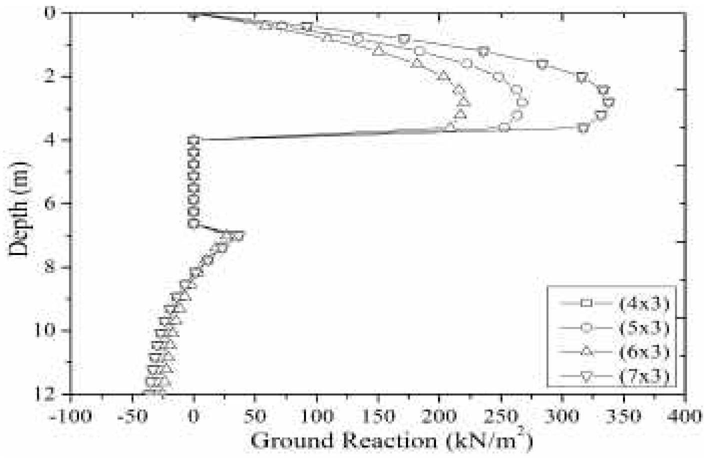

Fig. 8. Typical plot of Ground Reaction with depth for different arrangements (L-12m & D-1.0m)

6.3 Shear Force

Shear force are the summation of all vertical forces either left or right side of the section considered. For this case also the load subjected to pile is same as discussed above. The shear force also plotted to observe the effect of L/D and change in arrangement effect of piles. When diameter is decreasing as a result of which positive shear force is increasing and similarly with increase in number of pile, the shear force is decreasing. The reason behind increase in shear force is due to decrease in stiffness of pile member. The plot of different L/D and arrangements are shown in Fig. 9. and Fig. 10. respectively. Fig. 9. shows that, the shear force is maximum at the pile top for larger diameter of pile and also it remains almost constant after the first layer of soil (i.e. Fly ash) but for smaller diameter the nonlinearity is significant. Fig. 10. shows that, the change in maximum shear force is at the top of ground level only and becomes same after the thickness of first layer. Shear force is more dependent on location of pile in group and less on their group size.

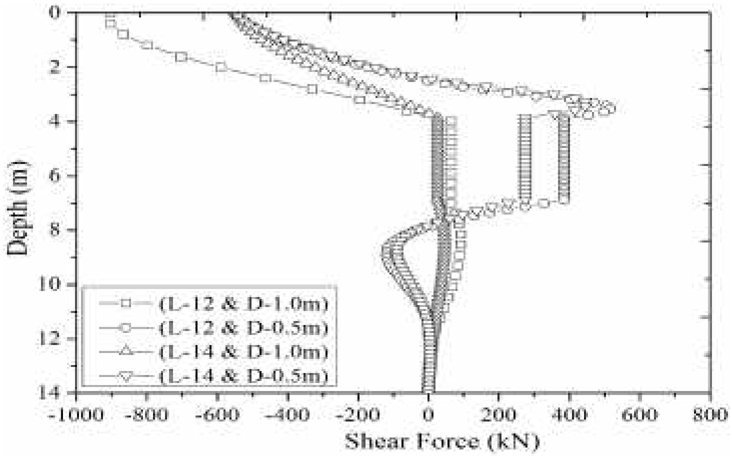

Fig. 9. Typical plot of Shear Force with depth for different L/D ratio (Arrangement – 7x3)

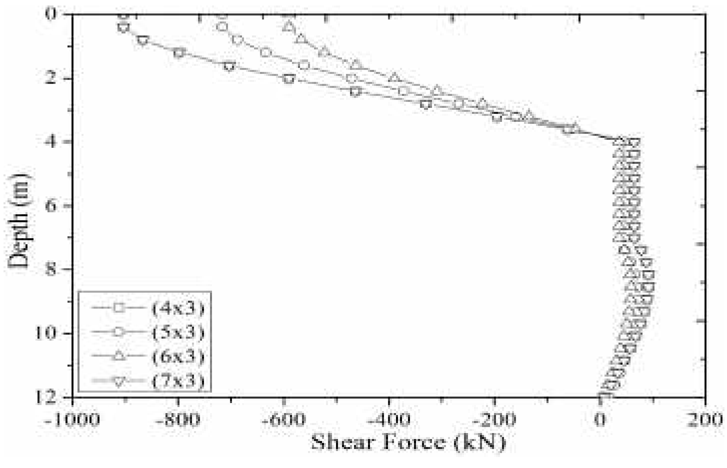

Fig. 10. Typical plot of Shear Force with depth for different arrangement (L-12m & D-1.0m)

6.4 Bending Moment

Bending moment is the moment induced into the member when external force/moment is applied to the member causing the member to bend. The load applied at the top of pile is same for all cases. The variation of bending moment with different L/D ratio and change in arrangement of piles are plotted to see their effects. The bending moment increases upto its peak at the top layer of soil because the effect of lateral load decreases with increase in depth of pile. And also for larger diameter the position of point of contra-flexure is at lesser depth whereas point of contra-flexure position increases with decrease in diameter. The plot of different L/D and arrangements are shown in Fig. 11. and Fig. 12. respectively. From Fig. 11, it can be seen that bending moment is increasing with decrease in pile diameter and length; this may be due to the reduction in pile resistance by decreasing the surface area of pile. Similarly, in Fig. 12, there is not much difference between the bending moment profile with depth for different pile group (i.e. 4x3 to 7x3), this occurs because the bending moment is independent of group size but it is function of position of pile within the group.

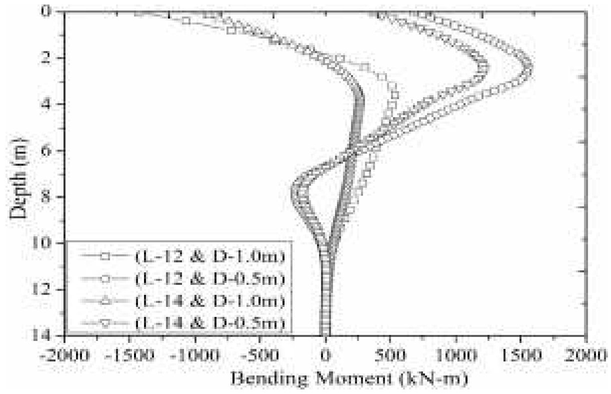

Fig. 11. Typical plot of Bending Moment with depth for different L/D ratio (Arrangement – 7x3)

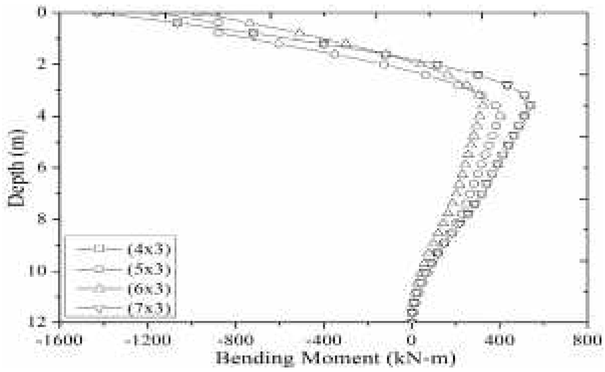

Fig. 12. Typical plot of Bending Moment with depth for different arrangements (L-12m & D-1.0m)

7 Conclusions

The P-Y analysis was performed to study the behavior of laterally loaded pile in stratified soil-ash system. The behavior of pile covers horizontal displacement, ground reaction, shear force and bending moment along the pile length. The effect of various parameters such as pile length and diameter or L/D ratio and change in arrangements of pile were considered. From the results of pile response the following conclusion can be drawn:

1) The P-Y curves are not truly nonlinear at lower depth but it becomes nonlinear as the depth increases.
2) The load-deflection plots increases nonlinearly with increase in L/D ratio and pile diameters.
3) The change in horizontal deflection is very small for small change in diameter of pile but it changes significantly with large change in diameter.
4) When length and diameter of pile is fixed then with increase in number of pile leads to the decrease in shear force and bending moment.
5) With increase in number of pile based on arrangement the ground reaction increases reaches to maximum and then decreases.

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