# Influence of Combined Vertical and Lateral Loading on Lateral response of Piled Raft Foundation

Plaban Deb[1] and Sujit Kumar Pal[2]

[1, 2] Civil Engineering Department, NIT Agartala, Tripura
plaban930@gmail.com, skpal1963@gmail.com

**Abstract:**
Due to the complexity involved in analyzing the piled raft foundation under combined loading, the existing design practice for the piled raft assumes that the influence of vertical and lateral loads are independent of each other and the experimental tests on the behaviour of piled raft foundation under the action of combined vertical and lateral loads are relatively scarce. Therefore, the objective of the present study is to examine the behaviour of piled raft foundation subjected to pure lateral loads and combined vertical and lateral loads through laboratory model tests. The experimental program includes the prototype model test on raft braced by 2 × 2 and 3 × 3 pile groups. The laboratory tests are performed in silty-clay soil underlain by sandy soil. Initially, the response of the piled raft foundation under pure lateral load is performed through laboratory model test and to understand the response of the piled raft foundation under combined loads, the influence of vertical loads equal to $0.25V_u$, $0.5V_u$, $0.75V_u$ and $0.9V_u$ are considered. The ultimate vertical load capacity ($V_u$) corresponding to the settlement of 10% of raft width is evaluated by a separate vertical load test. The results of the experiments have shown the significant influence of vertical loads on a pile's lateral response. For the structural design of piled raft, it is important to find out the bending moment developed in the pile in piled raft. Therefore, the influence of combined loading on the bending moment developed in the pile has been examined from the laboratory model test.

**Keywords:** Piled raft, Combined vertical and lateral loading, Ultimate vertical load capacity, Bending moment.

## 1 Introduction

Piled raft foundations are generally used when the isolated footing covers more than 70% of area under a super-structure and these are being used in several countries to sustain different kinds of super-structures, like buildings, bridges or industrial plants in various types of sub-soil. Using these foundation systems, differential settlement can be lowered to a great extent as piles improve the load carrying capability of the raft. In the piled raft foundation technique, the raft is directly contacted with the subsoil and hence a greater number of load exerts on the raft; thereby, making the method very tedious and also leads to the over design of the foundation. Although considering the settlement reduction, piled raft is a widely used foundation technique in today's world. The idea of using the pile as a settlement reducer was suggested by Burland et al. [1]. According to Horikoshi and Randolph [2], and Reul and Randolph [3] the strategic placement of the piles under the center of the raft can effectively decrease differential settlement under uniform loading condition. The effect of the variation in pile and raft geometry to determine the piled raft stiffness was studied through the centrifuge test on the piled raft system [4]. Furthermore, the analysis methods of the piled raft foundation are systematically summarized by Poulos [5] and a lot of experimental and numerical studies and field measurements on piled raft foundations have been accompanied to explore the settlement behaviour and the load sharing behaviour between raft and piles for vertical loading [6, 7]. All of the above research works are mainly concerned with piled raft foundations subjected to vertical loads only. A few researches have been worked on the behaviour of piled rafts subjected to lateral load. Pastsakorn et al. [8] performed small scale laboratory model test on the piled raft foundation under the action of horizontal loading in a 1g field. Hamada et al. [9] carried out large scale cyclic lateral loading test on the piled raft foundation to investigate the effect of vertical load during earthquake. Horikoshi et al. [10] performed a series of static vertical and horizontal load test on the piled raft foundation using a geotechnical centrifuge. Zhu et al. [11] studied the influence of vertical loading on the horizontal response of the disconnected piled raft through a series of 1g model test.

In the conventional design concept for pile groups, it is assumed that all lateral loads are carried by the piles only. But in the case of the piled raft foundation, the fact is that some of the load is transferred to the soil through the raft by friction. In the case of the piled raft subjected to the combined vertical and lateral loading, the bending moment developed in the piles is not only due to the shear force at pile heads but also due to the ground displacement caused by the raft friction. From the previous research works, it is understood that the behaviour of the piled raft foundation under the combined vertical and lateral load are rather limited. According to the current design practice of foundation in the field of geotechnical engineering, it is more rationally required to understand the behaviour of piled raft foundation subjected to combined load. Therefore, the main objective of the present study is to observe the effect of vertical load on the lateral response of the piled raft foundation.

## 2 Materials, Test Set-up and Test Procedure

### 2.1 Sub-soil Materials

In this study, silty-clay and sand are used as sub-soil materials. The physical and geotechnical properties of both the soil are evaluated according to ASTM codes. The index properties of silty-clay soil are obtained as liquid limit 46%, plastic limit 24% and plasticity index 22%. According to the Unified Soil Classification System (USCS), the silty-clay soil sample is categorized as low plasticity clay (CL). By performing several UCS test, the undrained shear strength ($S_u$) of silty-clay sample is found to be 10 kPa at the water content of 35% and corresponding soil density ($\gamma_{exptl.}$)

is found around 17.5 kN/m$^3$. The physical and geotechnical properties of clean dry sand are listed in Table 1 and the particle size distribution curve for both the soil is shown in the Fig.1.

**Table 1.** The physical and geotechnical properties of sand

| Physical properties | Test results |
|---|---|
| Specific gravity ($G_s$) | 2.64 |
| Effective grain size, $D_{10}$ (mm) | 0.37 |
| Mean grain size, $D_{50}$ (mm) | 0.85 |
| Coefficient of curvature ($C_c$) | 1.02 |
| Coefficient of uniformity ($C_u$) | 2.57 |
| Unified soil classification system | SP |
| Minimum void ratio ($e_{min}$) | 0.59 |
| Maximum void ratio ($e_{max}$) | 0.86 |
| Void ratio, at placement density ($e_{exptl.}$) | 0.67 |
| Minimum dry density, $\gamma_{min}$ (kN/m$^3$) | 14.20 |
| Maximum dry density, $\gamma_{max}$ (kN/m$^3$) | 16.60 |
| Placement dry density, $\gamma_{exptl.}$ (kN/m$^3$) | 15.80 |
| Relative density, $I_D$ (%) | 70 |

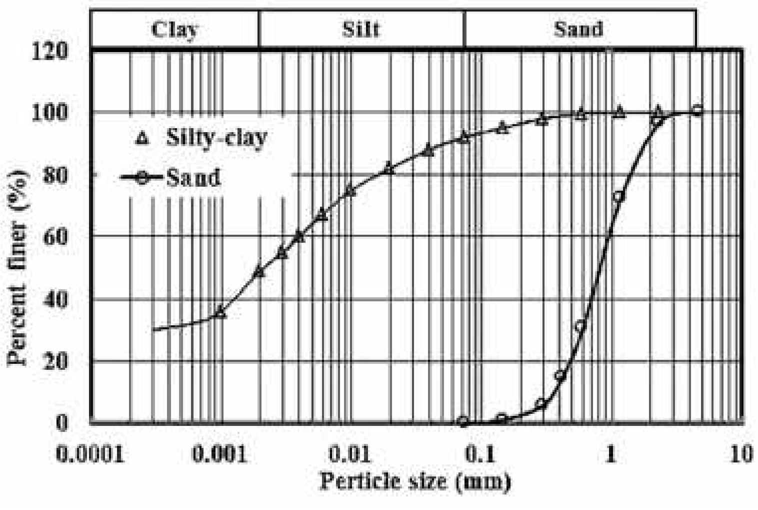



**Fig.1.** Particle size distribution curve

## 2.2 Model Raft and Pile

Mild steel plate of dimensions 250 mm × 250 mm × 10 mm is used as a model raft and steel hollow pipes with outer diameters of 20 mm is used as a model pile. The embedded length of the pile is 300 mm. Each pile is instrumented with six pairs of strain gauges to measure the axial strain and bending moment. Each strain gauge has a gauge factor of 2, and resistance of 350 Ω. Shear strain gauges are pasted near the each pile head for measuring the lateral load carried by the pile head. Epoxy resin is used to paste each strain gauge on the surface of pile. A waterproof coating of silica gel is used to cover the strain gauges. The location of each pair of strain gauge and shear strain gauge is shown in the Fig. 2. Each pile head is provided with a bolt of 20 mm in diameter and 10 mm in length. To fix the pile into the raft surface, screwed holes are provided in the raft surface with diameter equal to the outer diameter of the pile which ensures the rigid connection between the pile and raft.

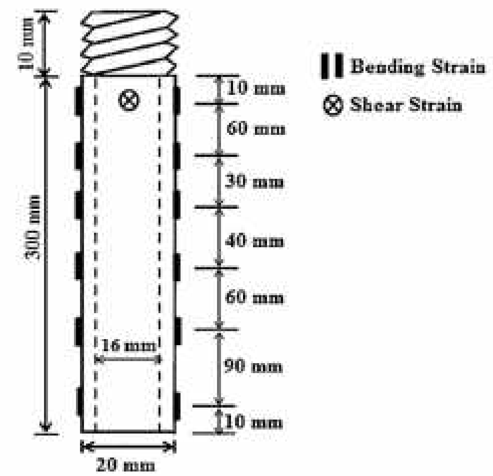
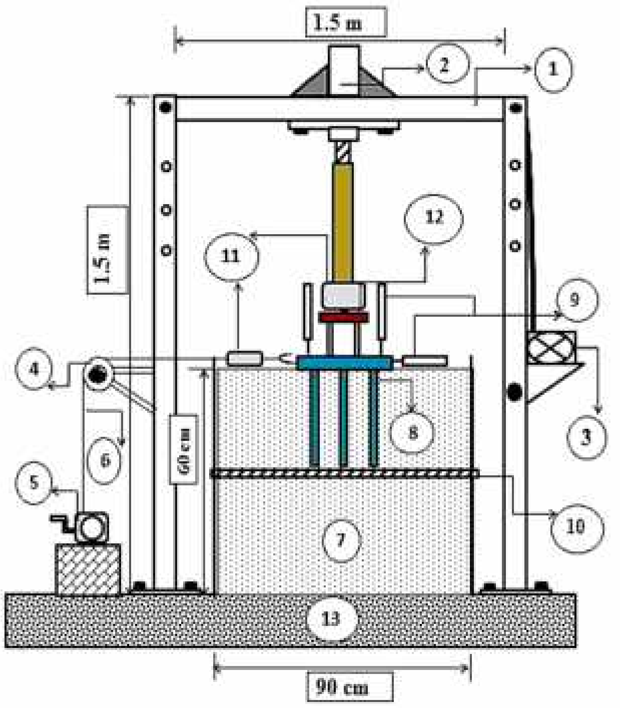



**Fig.2.** Model pile and location of the each pair of strain gauge

### 2.3 Testing Tank and Test Set-up

Testing tank is made of translucent Perspex-sheet and steel plates. To minimize the boundary effect of testing tank, the lateral boundary is taken 3.6 times the raft width and vertical boundary is taken around 2 times the embedded pile length. Therefore, the dimension of the testing tank is 90 cm long, 90 cm wide and 65 cm high. Four horizontal stiffeners are attached at the four side wall of the testing tank to avoid any bulging of the tank during the loading process. The combined vertical and lateral load test set-up is represented in Fig. 3. The vertical load is applied in the piled raft through a 5 ton capacity hydraulic jack and the lateral load is applied through a winch and a wire rope. A calibrated 30 kN capacity compressive load cell is attached to the hydraulic jack for measuring the applied vertical load and two calibrated LVDTs are used to measure the vertical deformations. The lateral load is measured using a calibrated 2 kN load cell and the lateral displacement is measured by two calibrated LVDTs.




1. Reaction Frame
2. Hydraulic Jack
3. Pumping Unit
4. Pulley
5. Winch
6. Wire Rope
7. Test Chamber
8. Model Piled Raft
9. LVDT
10. Horizontal Stiffeners
11. Load Cell
12. Loading Platform
13. Concrete base

**Fig.3.** Model test-set up

## 2.4 Test Program

A series of laboratory tests are performed to understand the effect of vertical load on the lateral behaviour of piled raft foundation. The 2×2 and 3×3 pile configuration with pile spacing to pile diameter ratio of 4 is used under the model raft to perform the laboratory test. The laboratory tests are performed in silty-clay soil underlain by sandy soil. Initially, the response of the piled raft foundation under pure lateral load is performed through laboratory model test and to understand the response of the piled raft foundation under combined loads, the vertical loads equal to $0.25V_u$, $0.5V_u$, $0.75V_u$ and $0.9V_u$ are considered. The ultimate vertical load capacity ($V_u$) corresponding to the settlement of 10% of the raft width is evaluated by a separate vertical load test. Therefore, total 12 tests are conducted in the laboratory. The program of laboratory model test on piled raft foundations are presented in Table 2.

**Table 2.** Laboratory test program on piled raft foundation

| Sl. No. | Model Configuration | s/d | Loading Sequence | |
|---|---|---|---|---|
| | | | Vertical Load | Lateral Load |
| 1. | Raft + 4 piles | 4 | Upto failure | – |
| | | | – | Upto failure |
| | | | $0.25V_u$, $0.5V_u$, $0.75V_u$ & $0.9\ V_u$ | Upto failure |
| 2. | Raft + 9 piles | 4 | Upto failure | – |
| | | | – | Upto failure |
| | | | $0.25V_u$, $0.5V_u$, $0.75V_u$ & $0.9\ V_u$ | Upto failure |

### 2.5 Test procedures

1. Each experimental test started with placing the sand in the testing chamber in layers (each of about 50 mm thick) by sand raining technique and the sand is poured up to a height of 450 mm. The sand is placed in the chamber with uniform relative density of 70%.
2. After the placing of sand, the silty-clay soil is placed in the test chamber up to a height of 600 mm at a constant density and water content. Dry silty-clay soil is thoroughly mixed with water content of 35% to get the required consistency ($I_c$= $w_L$-w/$I_p$= 0.49) of silty-clay lump. The mixed slity-clay lump is then placed in the testing chamber in 50 mm thick layers and tamped with a steel template to attain the required bulk density of 17.5 kN/m$^3$. After the completion of silty-clay bed preparation, the soil bed is covered with plastic sheet and is permitted to set at room temperature for about 24 to 30 hours to confirm the uniform circulation of the moisture content.
3. As the piles used in the piled raft are non-displacement piles, at first the soil is placed up to the tip of the piles. After that, the model piled raft is kept in the center of the test chamber and again soil is packed in the chamber up to the required height keeping the model piled raft in vertical position.
4. After that, the vertical load is applied to model piled raft through hydraulic jack at a loading rate of 1mm/min and vertical displacement is measured with the help of LVDTs. After the application of required level of vertical load, the lateral load is applied through a winch and a wire rope at a displacement rate of 0.25 mm/min. The lateral displacement is then recorded with the help of two horizontally placed LVDTs.

5. After completion of one test, all the piles, raft and the soil from the testing chamber are removed and the similar method is repeated for the consecutive tests.

## 3 Results and Discussions

### 3.1 Pure Vertical and Pure Lateral Load Test on Piled Raft

Fig. 4 shows the load-settlement response of different piled raft foundation under pure vertical load. From this load settlement response, the ultimate vertical load corresponding to the settlement of 10% of raft width for each piled raft configuration is evaluated. From the figure, it is observed that as the number of pile beneath the raft increases the vertical load carrying capacity is also increases. To understand the lateral response of piled raft foundation, the lateral load is applied up to the lateral deflection corresponding to10% of the pile diameter. The lateral load vs. normalized lateral deflection (y/d = 0.1) of different piled raft foundation subjected to pure lateral load is presented in Fig.5. It is observed from the figure that for same normalized lateral deflection, the raft with 9 piles exhibit higher lateral load as compared to the raft with 4 piles.

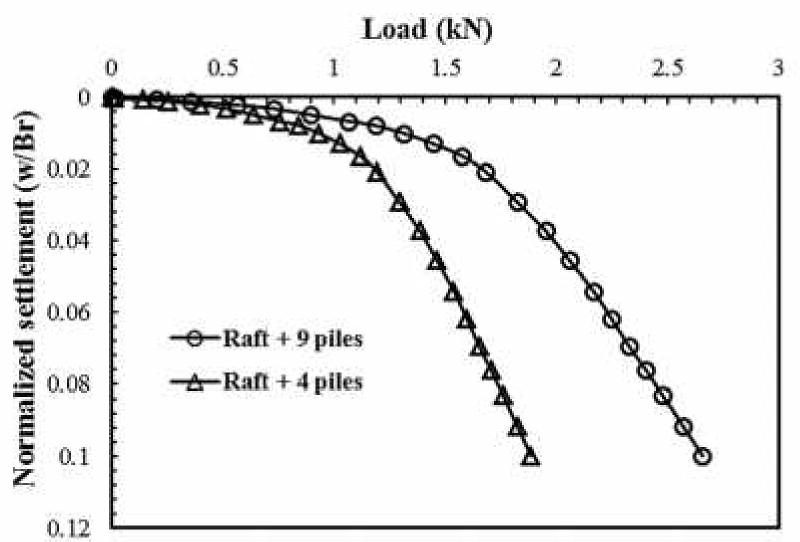



**Fig.4.** Vertical load vs. settlement curve

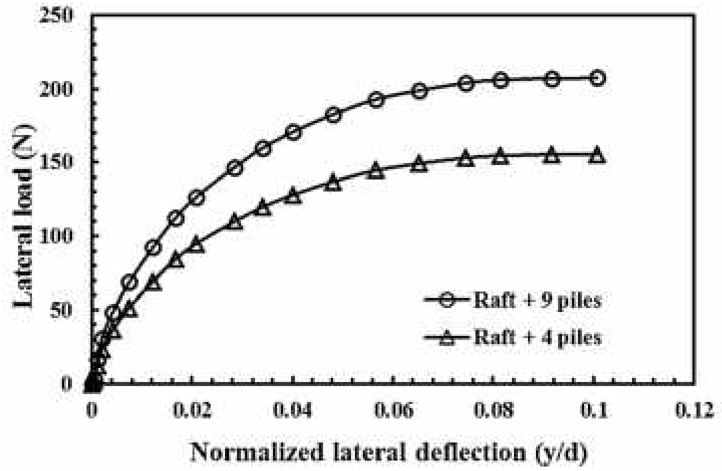



**Fig.5.** Lateral load vs. normalized lateral deflection curve

### 3.2 Effect of Vertical Load on the Lateral Response of Piled Raft

To observe the effect of vertical load on the lateral response of the piled raft foundation, the lateral responses of piled raft foundation at different level of vertical load are shown in Figs. 6 and 7. Form the figures, it can be concluded that at certain normalised lateral deflection, the lateral load carrying capacity of the piled raft foundation increases with the increase of the vertical load level. This increase is due to the increase in the confining stress developed in the soil below the raft with the continuous increase of the vertical load. When the applied vertical load is 90% of the ultimate vertical load, the lateral load carrying capacity of model configuration (raft + 9 piles) is increased about 46% as compared to pure lateral load and the lateral load carrying capacity of model configuration (raft + 4 piles) is increased by 30%.

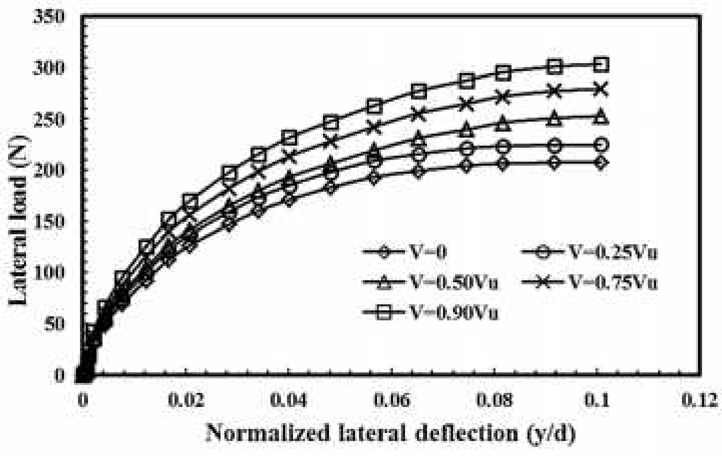



**Fig.6.** Lateral responses of piled raft (raft + 9 piles) at different vertical load

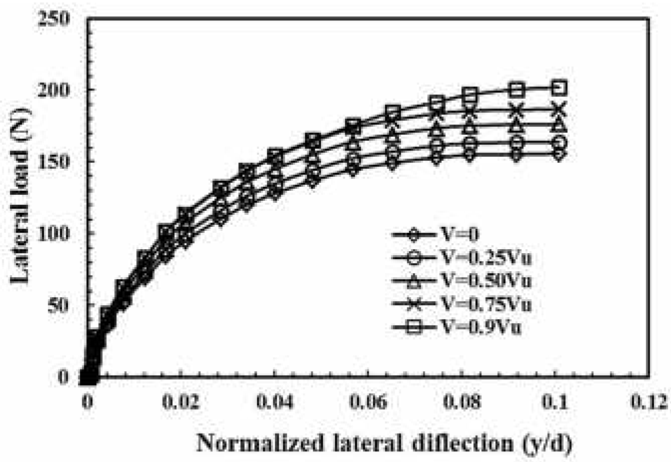



**Fig.7.** Lateral responses of piled raft (raft + 4 piles) at different vertical load

The lateral load carried by front row pile and rear row pile with the normalized lateral deflection for both the model configuration under pure lateral loading condition is shown in Fig.8. From the figure, it is found that the front row pile carries much higher lateral load as compared to the rear row pile. For the model configuration (raft + 9 piles), the front row pile takes about 41% to 45% of the total lateral load carried by the pile group, whereas in the case of (raft + 4 piles), the front row pile carries around 55% to 61% of the total lateral load carried by the pile group.

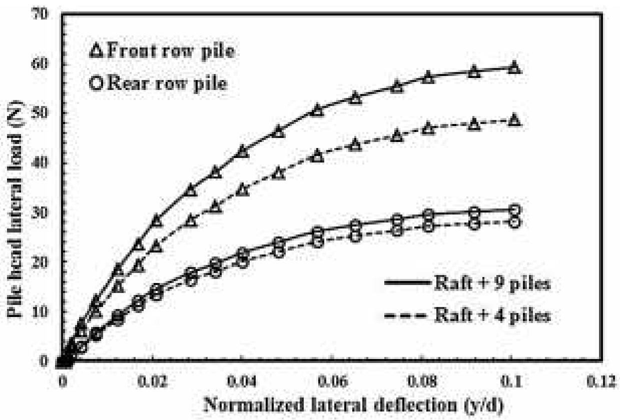



**Fig.8.** Pile head lateral load vs. normalized lateral deflection for each row pile

### 3.3 Bending Moment in the Pile

The bending moment developed in the pile can be evaluated as

$$M = \frac{E_P I_P \, (\varepsilon_t - \varepsilon_c)}{d}$$

where, $E_P$ is the modulus of elasticity of pile, $I_P$ is the moment of inertia of pile, $d$ is the pile diameter and $(\varepsilon_t - \varepsilon_c)$ is the difference between the strain in tension and compression face. The maximum positive and negative bending moment for different vertical load is shown in Fig.9. It is observed from the figure that the maximum positive and negative bending moment for both the model configuration increases with the increase of vertical load. The variation of the bending moment developed along the front row pile and rear row pile under pure lateral load is presented in Fig.10. The result obtained from the figure reveals that the bending moment is higher in the case of front row pile as compared to the rear row pile for both the model configuration. It is also observed from the figure that the maximum positive bending moment is developed almost at a depth of 0.5 times the embedded length of the pile from the pile head and the maximum negative bending moment is developed at the pile head.

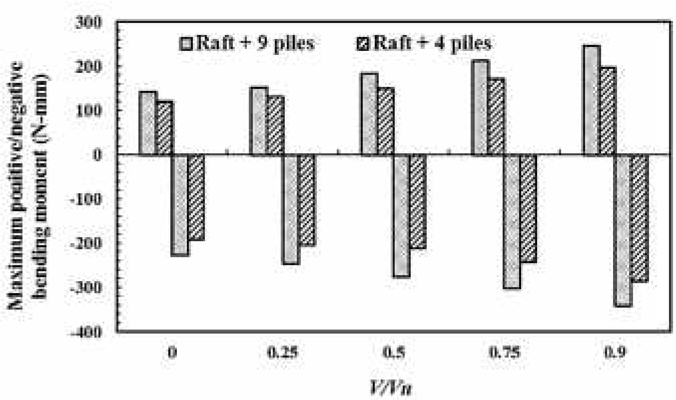



**Fig.9**. Variation of maximum positive and negative bending moment for different vertical load

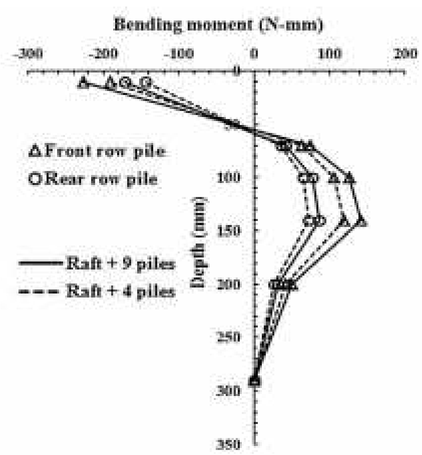



**Fig.10**. Variation of bending moment for each row pile

## 4 Conclusions

From the results of the experimental investigation on the behaviour of the piled raft foundation subjected to combined vertical and lateral loading condition, the following conclusions may be drawn:

1. Due to the increase of confining stress in the soil below the raft, the lateral load carrying capacity of piled raft foundation increases with the increase of vertical load. When the applied vertical load is equal to 90% of the ultimate vertical load, the lateral load carrying capacity of (raft + 9 piles) and (raft + 4 piles) is increased about 46% and 30% respectively, as compared to pure lateral load and the lateral load carrying capacity of piled raft foundation get enhanced by adding the number of piles below the raft.
2. The lateral load carrying capacity of the front row pile in model configuration (raft + 9 piles) is around 41% to 45% and model configuration (raft + 4 piles) is about 55% to 61% of the total lateral load carried by the pile group.
3. The maximum positive and negative bending moment increases with the increase of vertical load and the maximum positive bending moment is developed almost at a depth of 0.5 times the embedded length of the pile from the pile head, whereas the maximum negative bending moment is developed at the pile head.

## References


1. Burland, J.B., Brooms, B.B., de Mello, V.F.B.: Behavior of foundations and structures. Proc. 9 ICSMFE, Tokyo 2, pp. 495-546 (1977).
2. Horikoshi, K., Randolph, M.F.: Centrifuge modelling of piled raft foundation on clay. Geotechnique 46(4), pp. 741–752 (1996).
3. Reul, O., Randolph, M.F.: Design strategies for piled rafts subjected to nonuniform vertical loading. Journal of Geotechnical and Geoenvironmental Engineering 130(1), pp. 1–13 (2004).
4. Conte, G., Mandolini, A., Randolph, M.F.: Centrifuge modeling to investigate the performance of piled rafts. In: Van Impe WF (ed) Proceedings of the 4th international geotechnical seminar on deep foundations on bored and auger piles. Millpress, Rotterdam, pp. 359–366 (2003).
5. Poulos, H.G.: Piled raft foundations: design and applications. Geotechnique 51(2), 95-114 (2001).
6. Katzenbach, R., Arslan, U., Moormann, C.: Piled raft foundation projects in Germany. In: Design applications of raft foundations (2000).
7. Yamashita, K., Hamada, J., Onimaru, S., Higashino, M.: Seismic behavior of piled raft with ground improvement supporting a base-isolated building on soft ground in Tokyo. Soils Found. 52(5), 1000–1015 (2012)
8. Pastsakorn, K., Hashizume, Y., Matsumoto, T.: Lateral load tests on model pile groups and piled raft foundations in sand. In: Proceedings of International Conference Physical Modelling in Geotechnics, pp.709–714 (2002).

9. Hamada, J., Tsuchiya, T., Tanikawa, T., Yamashita, K.: Lateral loading tests on piled rafts and simplified method to evaluate sectional forces of piles. Geotechnical Engineering Journal of the SEAGS and AGSSEA 46(2), 29-42 (2015).
10. Horikoshi, K., Matsumoto, T., Hashizume, Y., Watanabe, T., Fukuyama, H.: Performance of piled raft foundations subjected to static horizontal loads. International Journal of Physical Modelling in Geotechnics 3(2), 37-50 (2003).
11. Zhu, X.J., Fei, K., Wang, S.W.: Horizontal loading tests on disconnected piled rafts and a simplified method to evaluate the horizontal bearing capacity. Advances in Civil Engineering. (2018).