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Lateral load sharing and response of piled raft foundation in cohesionless medium: An experimental approach

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Abstract. The piled raft foundations are subjected to lateral loading under the action of wind and earthquake loads. Their bearing behavior and flexural responses under these loadings are of prime concern for researchers and practitioners. The insufficient experimental studies on piled rafts subjected to lateral loading lead to a limited understanding of this foundation system. Lateral load sharing between pile and raft in a laterally loaded piled raft is scarce in literature. In the present study, lateral load–displacement, load sharing, bending moment distribution, and raft inclinations of the piled raft foundations have been discussed through an instrumented scaled down model test in 1 g condition. The contribution of raft in a laterally loaded piled raft has been evaluated from the responses of pile group and piled raft foundations attributing a variety of influential system parameters such as pile spacing, slenderness ratio, group area ratio, and raft embedment. The study shows that the raft contributes 28–49% to the overall lateral capacity of the piled raft foundation. The results show that the front pile experiences 20–66% higher bending moments in comparison to the back pile under different conditions in the pile group and piled raft. The piles in the piled raft exhibit lower bending moments in the range of 45–50% as compared to piles in the pile group. The raft inclination in the piled raft is 30–70% less as compared to the pile group foundation. The lateral load–displacement and bending moment distribution in piles of the single pile, pile group, and piled raft has been presented to compare their bearing behavior and flexural responses subjected to lateral loading conditions. This study provides substantial technical aid for the understanding of piled rafts in onshore and offshore structures to withstand lateral loadings, such as those induced by wind and earthquake loads.

Keywords: bending moment; lateral load; load sharing; raft inclination; pile group; piled raft;

1. Introduction

The foundations of offshore wind turbines, high rise buildings, suspension bridges, bridges across rivers, transmission towers, and jetty structures among many other important structures subjected to lateral loadings are built over either pile group or piled raft foundations. The pile group foundations are designed to carry the total load of the structure built over it ignoring the load carrying contribution of the pile cap, however, in a piled raft, the load carried by the structure is shared between both the components i.e., pile and raft (Katzenbach and Turek 2005, Hamada *et al.* 2015, Malviya *et al.* 2023). Significant studies have been conducted by researchers to understand the behavior of the pile group and piled raft foundations under vertical loading conditions considering different governing parameters and complex interactions (Fattah *et al.* 2013, Ghiasi and Moradi 2018, Amornfa *et al.* 2022). Several studies have been conducted by researchers to evaluate the responses of laterally loaded piles. The p–y method is widely used to analyze laterally loaded piles in which piles are assumed to behave as beams supported by a series of lateral soil springs (Shi *et al.* 2018). Zhang *et al.* (1999) conducted numerical analyses using the coupled bridge foundation–superstructure finite element code to investigate the behavior of laterally loaded single and group piles. Patra and Pise (2001) evaluated the ultimate lateral resistance of a pile group considering variables such as shape, size, spacing of the piles, and pile friction angle from laboratory model test. Chen and Chen (2008) evaluated the interaction factor between two laterally loaded piles in a pile group considering the influence of pile spacing, pile–soil stiffness ratio, pile slenderness ratio, and departure angle of the loading direction. Gupta and Basu (2017) developed a continuum–based method for the laterally loaded piles embedded in multilayered heterogeneous elastic soil to evaluate pile displacement, rotation, and maximum bending moment. Limited studies have been conducted to evaluate the responses of piled raft foundations subjected to lateral loading condition. Pastsakorn *et al.* (2002) compared the behavior of the pile group and piled raft from a small scale test and observed that the piled raft experiences higher lateral resistances as compared to the pile group foundations. Fukumura *et al.* (2003) conducted shaking table test on model piled raft and model pile group foundations at 1 g gravitational field and observed that the horizontal stiffness and the horizontal

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Table 1 Previous typical experimental studies on piled rafts subjected to lateral loading

	Pile arrangement	Dimension of pile			Dimension of raft			Dimension of tank			Boundary conditions	
		L_P	D_P	S_P (x D)	L_R	W_R	T_R	L_T	W_T	D_T	L_B	V_B
Pastsakorn *et al.* (2002)	2x2, 3x3	200	20	3.75-7.5	75, 150, 225	75, 150, 225	22	840	500	300	1.37–5.10	0.50
Horikoshi *et al.* (2003)	2x2	250	10	4	80,120	80,120	30	700	700	470	2.42–3.88	0.88
Matsumoto *et al.* (2004)	2x2	170	10	4	80	80	20	700	700	470	3.88	1.76
Katzenbach and Turek (2005)	5 piles	640	30	6	280	280	40	1000	1000	1180	1.29	0.84
Sawada and Takemuru (2014)	3x2	160	10	5	80	80	20	800	800	230	4.5	0.44
Hamada *et al.* (2015)	4x4	650,1100	19,76	13	1000	1000	500	2500	2500	8000	0.75	6.27, 11.31
Jamil *et al.* (2023)	2x2, 3x3, 5x5	457	19.05	3.33,6.67	304	304	25	914	1220	1524	1.00	2.33

resistance of the piled raft in the static horizontal load test were larger than that of the pile group. Sawada and Takemura (2014) conducted static horizontal load test using centrifuge model tests and observed that the horizontal resistance of the pile part in the piled raft foundation is higher than those observed in the pile group foundation due to raft base contact pressure. Hamada *et al.* (2015) investigated the responses of large–scale piled rafts subjected to static cyclic lateral loadings and observed that most of the lateral forces were carried out by the raft friction. Stacul *et al.* (2020) developed a code for analysis of laterally loaded piled raft foundation considering the nonlinear behavior of the reinforced concrete pile and the soil. Tarenia and Patra (2022) investigated the performance of laterally loaded piled raft foundations and observed that the bending moment in piles of connected piled raft foundations is about 1099–1081% higher than that in the piles of disconnected piled raft foundations. Jamil et al. (2023) compared the behavior of front and back piles in pile group and piled raft subjected to lateral loading using small scale model pile group and piled raft foundations in cohesionless medium and observed that the front pile experiences higher resistance as compared to the back pile.

The comparison of the behavior of single pile, pile group, and piled raft foundations subjected to lateral loading is very limited in the literature. The relative load sharing between pile and raft in a piled raft system, raft inclination, and the influence of different governing parameters on its bearing behavior and flexural responses are scarce in literature which motivates to conduct a detailed laboratory investigation on these foundations. In the present study, a series of experimental studies on laterally loaded model single pile, pile group, and piled raft in cohesionless medium is performed under 1 g conditions. The 1 g model tests are widely used to investigate the influence of governing parameters on the responses of different foundations due to convenience and associated economy (Prasad and Chari 1999). The piles are sufficiently instrumented to evaluate the bending moment distribution in the pile during progressive lateral loading. The behavior of model foundations in particular such as load–displacement, load sharing, and raft inclination has been investigated in detail attributing the influence of different parameters such as pile spacing, slenderness ratio, group area ratio, and embedment depth of the foundation. The range of load sharing between pile and raft in laterally loaded piled raft obtained from detailed experimental investigations has been presented. The load sharing obtained in the present study has been compared with the load sharing obtained from the limited experimental and analytical studies available in the literature and found to be in close range.

2. Experimental setup

2.1 Test tank

The test tank of dimension 1600 mm × 1250 mm × 1250 mm has been used. Different levels of the tank have been stiffened with steel channels to eliminate possibilities of volume change during the tank filling and subsequent applications of loadings during the test. Therefore, the test tank has rigid boundaries on all sides except on the top surface. Table 1 shows the summary of lateral load tests from a few of the previous studies and the respective boundary conditions adopted in their study. The lateral boundary varies in the range of 1 to 5.1 times the raft width and the vertical boundary varies in the range of 0.44 to 11.30 times the pile length respectively. In the present study, the lateral and vertical boundaries of the test tank are greater than 5 times the raft width and 0.6 times the pile

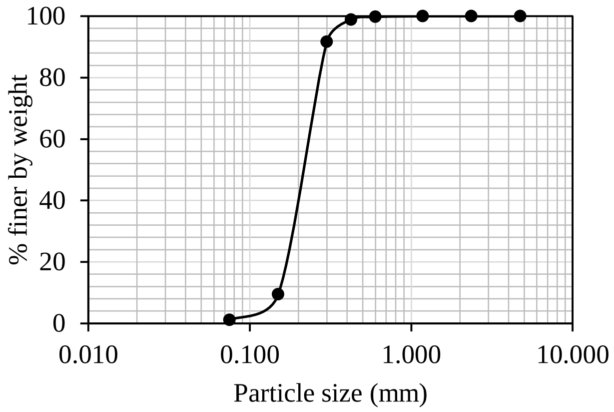


Fig. 1 Grain size distribution curve

Table 2 Properties of the sand

Sand (%)	98
Silt (%)	2
Clay (%)	0
D_{10}	0.13
D_{30}	0.18
D_{60}	0.23
Specific gravity	2.67
Coefficient of uniformity (C_u)	1.77
Coefficient of curvature (C_c)	1.08
Maximum density (g/cc)	1.66
Minimum density (g/cc)	1.39
Angle of internal friction (°) [RD = 80%]	36
IS classification	SP

length from the pile tip, respectively, and are sufficient to minimize the boundary effect (Pastsakorn *et al.* 2002, Hamada *et al*. 2015, Malviya and Samanta 2024a).

2.2 Material properties

2.2.1 Sand

The locally mined Solani river sand has been used in the present study. Different laboratory tests following Indian standards have been used to estimate the soil properties. The soil is mostly composed of coarse grain particles (98%) with the negligible presence of fine–size particles (2%) and is classified as poorly graded sand (SP). Fig. 1 shows the grain size distribution curve. The vibratory table has been used to evaluate the maximum and minimum density. Table 2 summarizes the properties of the sand. The sand used in the present study is white–grey in color and of smooth, rounded, and fine quality. This sand is widely available in the Indo–Gangetic plain region of India.

2.2.2 Characteristics of model pile and raft

Two different close–ended hollow circular piles of length 500 mm and 1000 mm having an outer diameter of 20 mm with wall thicknesses of 1 mm have been used as model piles. The classification of the piles used in the present study has been evaluated by calculating the stiffness factor (T) as per Indian standards (IS 2911 Part 1 2010). Based on the calculations the stiffness factor has been evaluated as T = 0.44 m and the piles have been classified as short (L_P = 500 mm) and intermediate (L_P = 1000 mm) piles.

Two different rafts of 200 mm x 200 mm x 10 mm and 300 mm x 300 mm x 10 mm have been used. The nut and bolt have been used to connect the pile with the raft ensuring rigid connection between them. The raft has been connected with two aluminum strips as a base for dial gauges to measure the lateral movement of the foundations during loading. The design and interpretation of the physical models require the evaluation of a set of laws of similitude that will tie the model to the prototype (Vu *et al.* 2018). The empirical relationship shown in Eq. (1 has been used to determine the range of prototypes for various scale factors (Wood *et al.* 2002).

$$(EI)_p / (EI)_m = n^5 \tag{1}$$

where n is the scale factor; $(EI)_p$ and $(EI)_m$ are the flexural rigidity of the prototype and model foundation, respectively. For an assumed M25 grade prototype reinforced cement concrete pile of diameter 0.50 m and raft having a depth of 0.50 m, the scaling factor is estimated as 14.50 and 48.50 respectively. The scaling factor replicates the pile of length 7 m and 15 m and the raft having dimensions of 10 m x 10 m x 0.5 m respectively. Similar dimensions of pile and raft have been used for the piled raft foundations in the field (Yamashita *et al*. 2011). The experimental studies revealed that the structural measurement (pile and raft) of 20–30 times the mean particle size of soil helps eliminate scaling effects. Ovesen (1979) observed the behavior of the model foundation obtained from centrifuge experiments having a ratio of raft diameter to the maximum grain size in the range of 24–133, coinciding with the prototype scale. Nicola and Randolph (1997) observed minor scaling deficiencies, with a ratio of pile diameter to grain size of 11. Vu *et al*. (2018) observed negligible influence of boundaries with the ratio of pile diameter to the grain size to be 40, during model tests in 1 g conditions. Jamil *et al*. (2023) conducted model tests in 1 g conditions on the laterally loaded piled raft and observed that the influence of grain size is negligible with the ratio of pile diameter to grain size to be 42. In the present study, the pile diameter and raft length ratio to the maximum grain size are 50 and 500, respectively. Based on the observations of previous studies, it can be concluded that the influence of the grain size on the responses of the foundation system in the present case will be negligible.

2.3 Instrumentation and data storage

The piles in every test have been instrumented with strain gauges of 120 Ω gauge resistance and gauge factor of 2.13. Fig. 2 shows the instrumented pile used in the study. The strain gauges are pasted at 0.05 L_P, 0.25 L_P, 0.50 L_P, 0.75 L_P, and 0.97 L_P to measure the strain distribution along the pile length. The strain gauges are connected to instrumentation lead wires using the TMS's TF–2S connecting terminals of dimensions 6 mm x

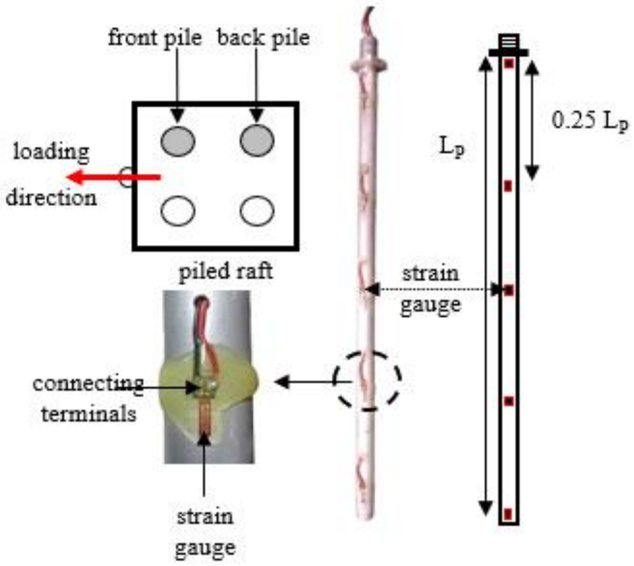


Fig. 2 Instrumented pile in piled raft subjected to lateral load.

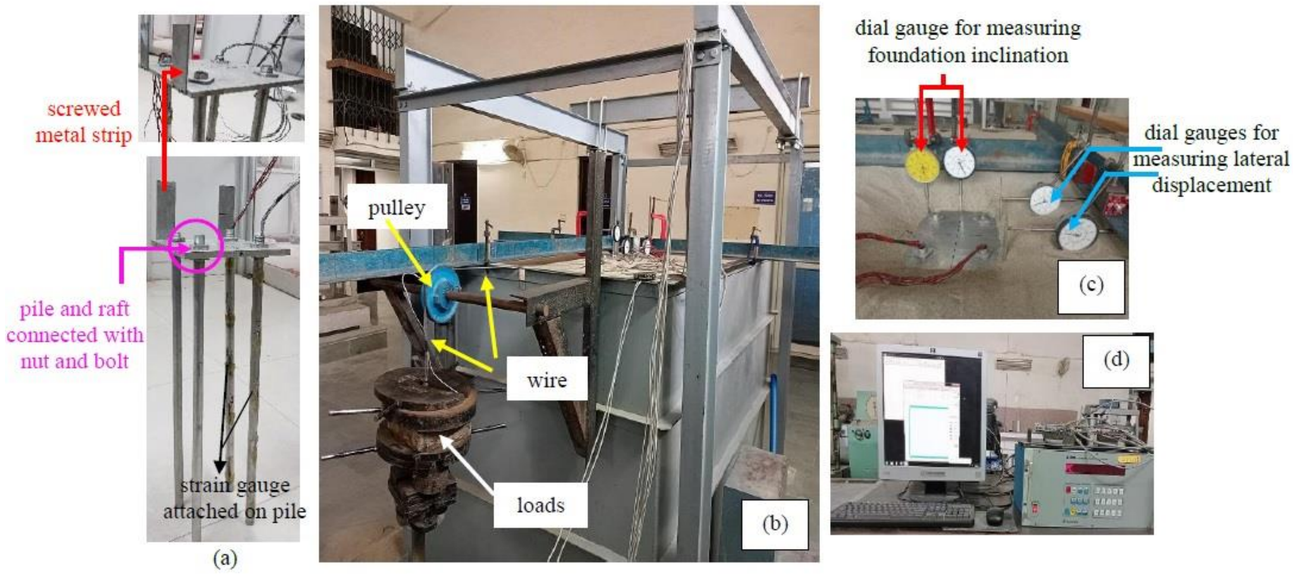


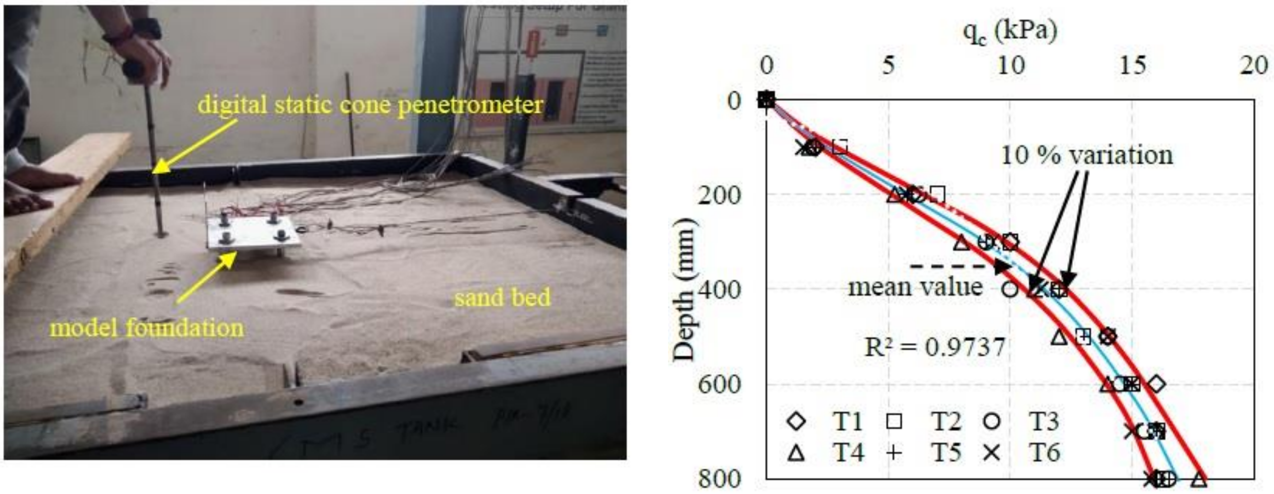
Fig. 3 Experimental setup for lateral load testing of model foundations: (a) instrumented piled raft, (b) test tank, (c) piled raft mounted with dial gauges and (d) data acquisition system

5.3 mm x 0.2 mm and could be operated at a temperature in the range of –196ºC to 180ºC. The 48–channel data acquisition system (DAS) comprising a data logger, display unit (computer), and a communication port has been used for continuously recording the strain along the front and back pile during the test. Four analog dial gauges with 50 mm travel and capable of measuring displacement to an accuracy of 0.01 mm have been used in the present study. Two dial gauges are mounted over the raft to evaluate the raft inclination and two dial gauges are placed to estimate the lateral displacement of the model foundations.

2.4 Test procedure

2.4.1 Preparation of sand medium and installation of single pile, pile group, and piled raft

The sand bed has been prepared considering dense conditions corresponding to a relative density of 80% for all the tests, which utilizes a total of 3867 kg of sand. The tank has been filled in layers of 50 mm height to achieve uniform density. The desired weight of the sand is poured uniformly into the respective layer, followed by compaction using a hammer. The tank is filled up to the pile tip initially and then its position on the sand is located and imprinted using the plumb bob. The model foundation is placed at their respective positions and kept vertical with the help of the holding device and then sand is poured to fill the tank simulating the bored cast–in–place piles. In single pile and pile group foundations, the pile cap is not in contact with the ground surface, whereas in piled raft foundations the pile cap is contact with the ground surface



(a) (b)

Fig. 4 DSCP results obtained from different tests

Table 3 Experimental Program

Test No.	FT	L_R (mm)	L_P (mm)	D_P (mm)	N_P	L_R/L_P	L_P/D_P	S_P/D_P	A_g/A_r	E_m (mm)
T1	SP	–	500	20	1	–	25	–	–	0
T2	SP	–	1000	20	1	–	50	–	–	0
T3	PG	–	500	20	4	–	25	6	–	0
T4	PG	–	1000	20	4	–	50	6	–	0
T5	PG	–	1000	20	4	–	50	3	–	0
T6	PR	200	1000	20	4	0.20	50	3	0.031	0
T7	PR	300	1000	20	4	0.30	50	6	0.013	0
T8	PR	200	500	20	4	0.40	25	6	0.031	0
T9	PR	200	500	20	4	0.40	25	6	0.031	50
T10	PR	200	500	20	4	0.40	25	6	0.031	100
T11	PR	200	1000	20	4	0.20	50	6	0.031	0
T12	PR	200	1000	20	4	0.20	50	6	0.031	50
T13	PR	200	1000	20	4	0.20	50	6	0.031	100

(Malviya and Samanta 2024b). Fig. 3 shows the instrumented piled raft, test tank with embedded foundations, positions of dial gauges, and data acquisition system. The miniature digital static cone penetrometer (DSCP) having a diameter of 20 mm and an apex angle of 60° has been used to ensure the uniform density of the prepared sand bed (Pastsakorn *et al.* 2002, Vu *et al*. 2018). Fig. 4(a) shows the DSCP test during the experimental investigations and Fig. 4b shows the typical variation of cone tip resistance (q_c) with depth at distinct locations within the tank during different tests. The results show that the cone tip resistance increases with the depth, this is because the overburden stress increases with depth. The DSCP test has been performed during the initial six tests to ensure the accuracy of the adopted methodology in the present study for preparing the sand bed with desired uniform relative density. The variation of cone tip resistance is observed to be within ±10 % of the mean value which ensures the uniformity of the prepared sand bed.

The results of the DSCP obtained from the initial test assure that the methodology adopted in the present study for preparing the sand bed of desired uniform relative density is appropriate.

2.4.2 Test program

A total of thirteen tests have been carried out on different model foundations. Table 3 shows the testing schemes of the present study. Different influencing parameters such as slenderness ratio (L_P/D_P), pile spacing (S_P/D_P), group area ratio (A_g/A_r), and depth of embedment (E_m) have been varied in the range of 25–50, 3D–6D, 0.013–0.031 and 0–100 mm respectively. The lateral loading has been applied in steps through dead weights using a wire attached to the foundation through a pulley system. Lateral displacements of 15–20% pile diameter have been observed to generate ultimate capacities in pile group (Broms 1964) and piled raft (Pastsakorn *et al.* 2002) foundations. In the present study, the tests have been conducted in load controlled manner and have been terminated at the foundation lateral displacement (u_x) corresponding to 20 % of the pile diameter i.e., $u_x/D_P = 20$.

3. Results and discussion

In this section lateral load–displacement, load sharing, moment distribution, and raft inclination have been discussed in detail. The total resistance of the piled raft foundation is the sum of the lateral resistance of the raft and the sum of the lateral resistances of the piles as shown in Eq. (2).

$$PR_L = \sum P_L + R_L \tag{2}$$

where, PR_L – lateral resistance of piled raft, ΣP_L – lateral resistance of piles, and R_L – lateral resistance of raft. The moment distribution along front and back piles of pile group and piled raft has been evaluated from the strain gauge readings using the bending equation (Nasr 2014) as per Eq. (3).

$$M = {E_P I_P \varepsilon}/{D_P} \tag{3}$$

where E_P is the elastic modulus of the pile, I_P is the moment of inertia of the pile, ε is the strain distribution and D_P is the pile diameter. The elastic modulus of the pile has been evaluated from the bending test (Lee and Chiang 2007).

3.1 Effect of pile spacing

The effect of pile spacing on load settlement and load sharing behavior of the piled raft foundation has been evaluated from the responses of single pile, pile group and piled raft foundations. Fig. 5(a) shows that the piled raft shows higher lateral resistance as compared to the pile group and varies in the range of 28–29% and 29–33% for u_x/D_p = 0 to 8% and 8 to 20% respectively. The increase in the overall lateral resistance of the piled raft as compared to the pile group is due to the contribution of additional raft base resistance (Sawada and Takemuru 2014). The lateral resistance carried by the pile group is 2–15% lower than the cumulative lateral resistance of four single piles. The pile–pile interaction between piles placed in groups leads to a reduction in the capacity as compared to the cumulative capacities of identical single piles (Tomlinson and Woodward 2007). Fig. 5b shows lower bending moments in the piles in the piled raft as compared to piles in pile group and single pile respectively. The load in the pile group is resisted by all the pile incorporating group action without any contribution from the raft. The raft significantly resists the lateral load in the piled raft foundation. For the same magnitude of applied load at the single pile, pile group and the piled raft, the piled raft foundation will undergo minimum lateral displacement as compared to pile group and single pile. Also, an increased stiffness and strength of the soil surrounding the piles beneath the raft due to the load transfer through the raft base to soil has been reported (Pastsakorn *et al*. 2002). All of these causes the lower bending moment in the piles of pile raft as compared to pile group and single pile. A similar trend has been observed by Teramoto and Kimura (2016). In the present study, the maximum bending moment for intermediate pile and short pile has been observed around 2.2–2.5L_P and 4–5L_P respectively. The behavior of short and intermediate piles subjected to lateral loadings are different due to their deformation mechanism. In a short pile, the pile rotates with respect to a point located close to its toe, whereas in an intermediate pile, the pile rotates and translates subjected to lateral load (Broms 1964, Prasad and Chari 1999). Broms (1964) observed a maximum bending moment around 4–5L_P in a short pile embedded in a cohesionless medium. Boominathan and Ayothiraman (2007) observed a maximum bending moment around 5–6L_P in a short pile embedded in a cohesive medium. Zhu *et al*. (2012) observed the maximum bending moment around 2.1–2.4L_P in laterally loaded intermediate piles during field investigations. Hamada (2015) observed the maximum bending moment around 2.5–3.2L_P on laterally loaded long piles during centrifuge studies on pile groups and piled raft foundations in cohesionless medium. Figs. 5(c) and 5(d) show that the front piles exhibit higher bending moments in both the pile group and piled raft foundations.

The front pile experiences 24–39% and 22–27% higher bending moments as compared to the back pile in the pile group and piled raft foundation respectively. The front and back piles in the piled raft exhibit 49–69% and 43–51% lower bending moments as compared to the corresponding pile in the pile group foundation. The lower bending moment in the back pile is attributed to the development of less lateral resistance due to the pile in front of it, commonly known as the shadowing effect (Zhang *et al.* 1999). Due to the rigid fixity of the pile at the top with the raft, the curvature is being developed at the top during lateral loading on the foundation consequently resulting in a negative bending moment at the pile head (Rollins and Stenlund 2010). Fig. 5(e) shows the variation of normalized bending moment (N_M) with u_x/D_P. The maximum bending moment of the pile group and piled raft has been normalized with the maximum bending moment of a single pile at the same u_x/D_P. The N_M in the front piles of the pile group and the piled raft is lower than that of the back piles affirming higher bending moments in the front piles. The N_M initially increases for u_x/D_P = 0–5% in the range of 0.84–0.90 and 1–1.20 in front and back piles of pile group respectively and becomes constant for u_x/D_P = 5–20%. A similar trend has been observed in piles of piled raft foundation, the N_M initially increases for u_x/D_P = 0–6% in the range of 0.80–1.15 and 1.05–1.35 in front and back piles of pile group respectively, and becomes constant in the range of u_x/D_P = 6–20 %. Fig. 6(a) shows that the lateral resistance of the piled raft is higher than the pile group and varies in the range of 44–49% and 40–43% for u_x/D_P = 0 to 8% and 8 to 20% respectively. The lateral resistance of the pile group is 0.5–9% lower than the cumulative lateral resistance of four single piles.

The responses of the foundations have been compared for two different pile spacing. The lateral resistance of the

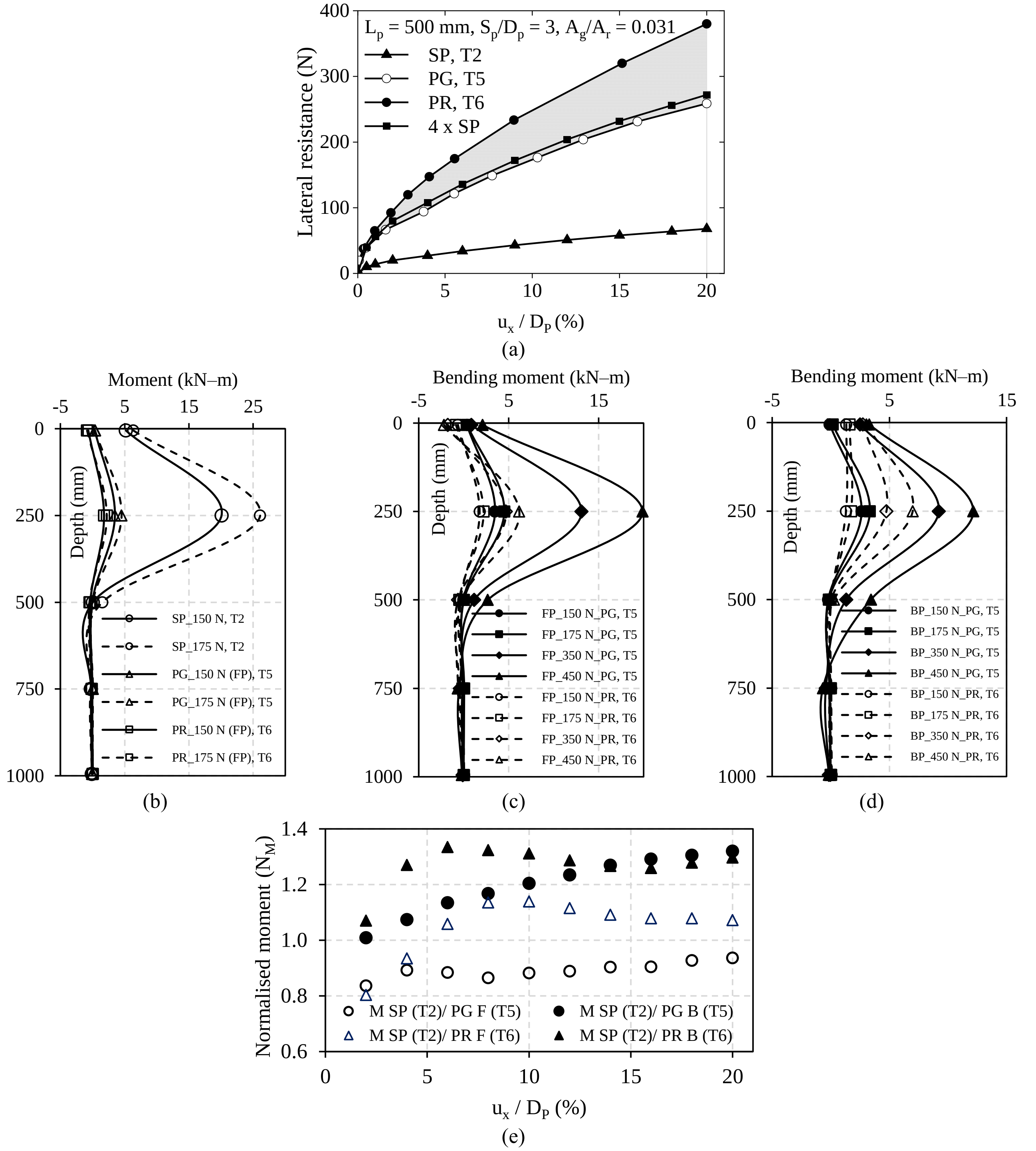
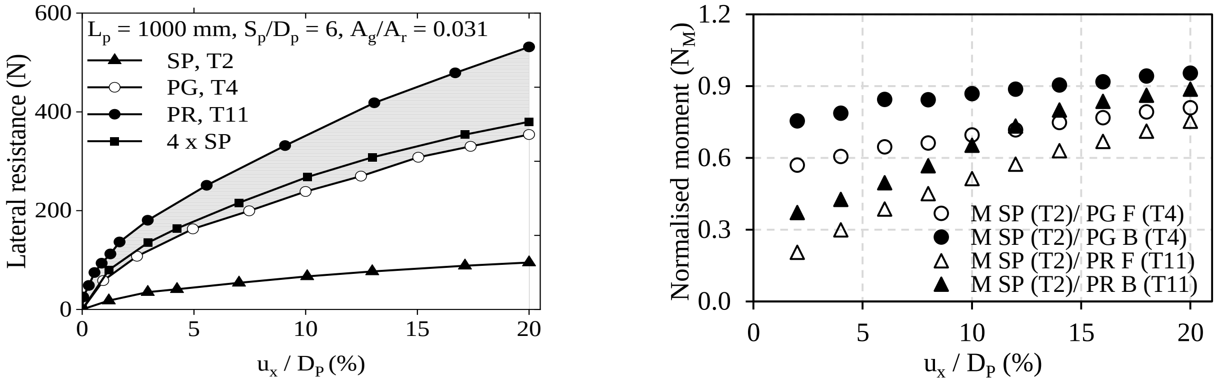


Fig. 5 Responses of foundation (S_P/D_P = 3): (a) load–settlement of SP, PG, and PR, (b) moment distribution in SP, PG, and PR, (c) comparison of moment distribution in front pile of PG and PR, (d) comparison of moment distribution in back pile of PG and PR and (e) normalized moment distribution in front and back pile in PG and PR

pile group increases in the range of 6–10% and 10–15% for u_x/D_P = 0 to 8% and 8 to 20 % whereas the lateral resistance of piled raft increases in the range of 28–33% and 24–28% for u_x/D_P = 0 to 8% and 8 to 20% with increasing the pile spacing from 3D to 6D respectively. The increase in lateral resistance of the foundations with increasing pile spacing is attributed to reduced stress overlapping of the individual piles (Pastsakorn *et al.* 2002, Rollins *et al.* 2006). Fig. 6(b) shows that the N_M initially increases rapidly for u_x/D_P = 0–10% in the range of 0.55–0.70 and 0.75–0.85 in front and back piles of pile group respectively and increases insignificantly for u_x/D_P = 10–20%. A similar trend has been observed in piles of piled raft foundation, the N_M initially increases rapidly for u_x/D_P = 0–14% in the range of 0.20–0.60 and 0.35–0.80 in front and back piles of pile group respectively, and increases insignificantly in the



(a) (b)

Fig. 6 Responses of foundation (S_P/D_P = 6): (a) load–settlement of SP, PG, and PR and (b) normalized moment distribution in front and back pile in PG and PR

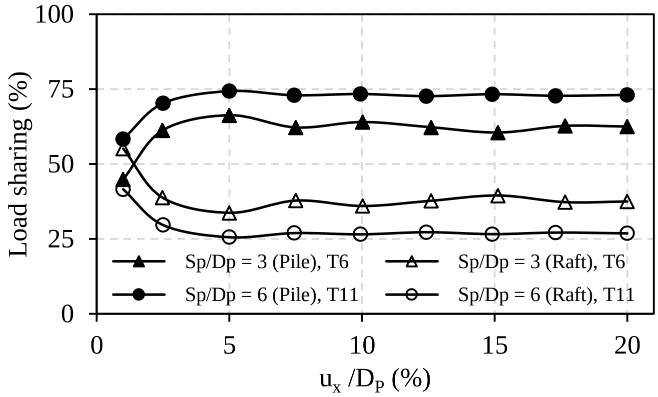
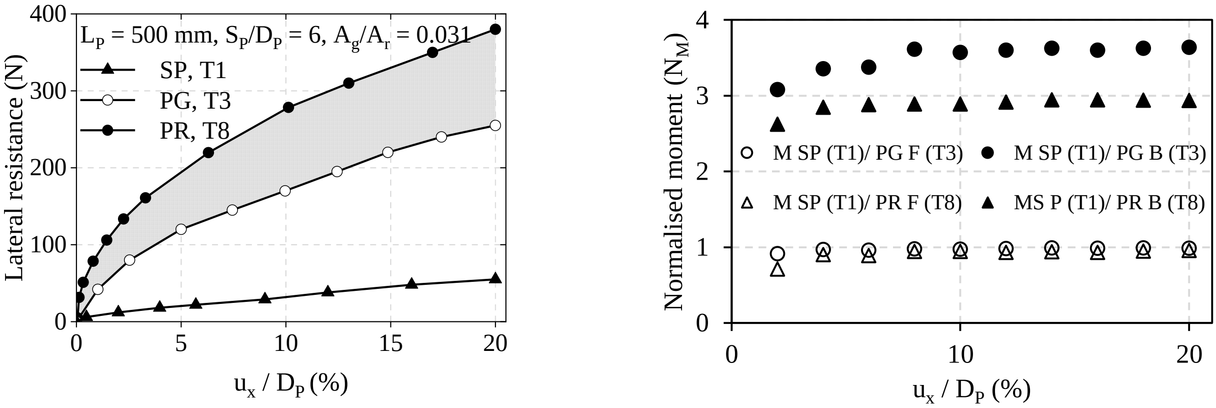


Fig. 7 Influence of pile spacing on lateral load sharing behavior of piled raft.



(a) (b)

Fig. 8 Responses of foundation (L_P = 500 mm): (a) load–settlement of SP, PG, and PR and (b) normalized moment distribution in front and back pile in PG and PR

range of u_x/D_P = 14–20%. Fig. 7 shows that during the initial state of lateral loading up to u_x/D_P = 2% the raft load sharing is 5 % higher than the pile load sharing for piled raft with S_P/D_P = 3. However, for u_x/D_P = 2–4%, the load carried by piles significantly increased whereas the load carried by raft decreased accordingly and the proportion of lateral load carried by the raft became lower than that of the piles. The lateral pile load sharing varies in the range of 45–70 % for u_x/D_P = 1–4%. The load–sharing ratio became almost constant beyond u_x/D_P = 4% and varies in the range of 65–70%. The pile load sharing increases in the range of 5–8%, and 8–20% for u_x/D_P = 1–4%, and 4–20% respectively with increasing pile spacing from 3D to 6D.

3.2 Effect of slenderness ratio

Fig. 8(a) shows that the piled raft experiences higher lateral resistance as compared to the pile group and the

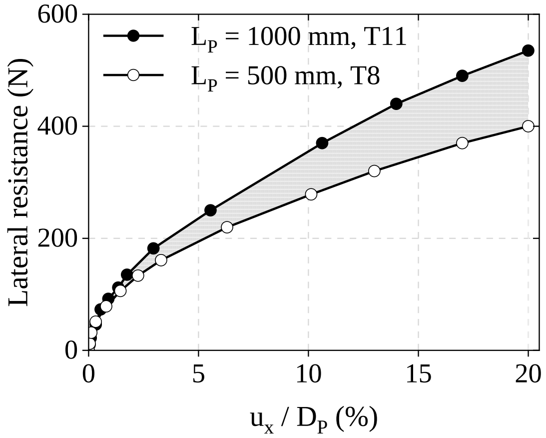


Fig. 9 Influence of pile length on lateral resistance of piled raft foundation.

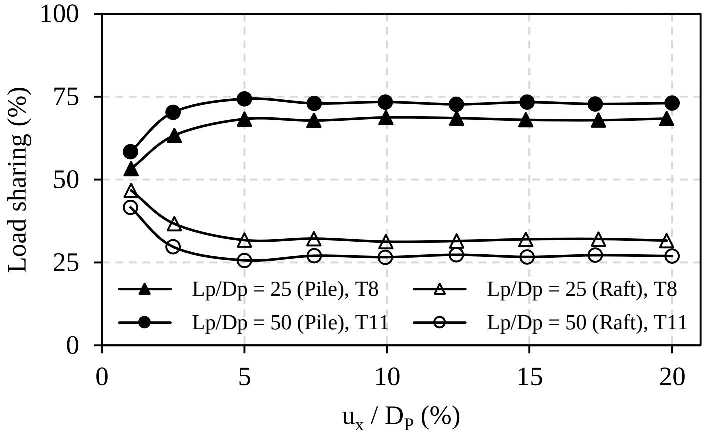


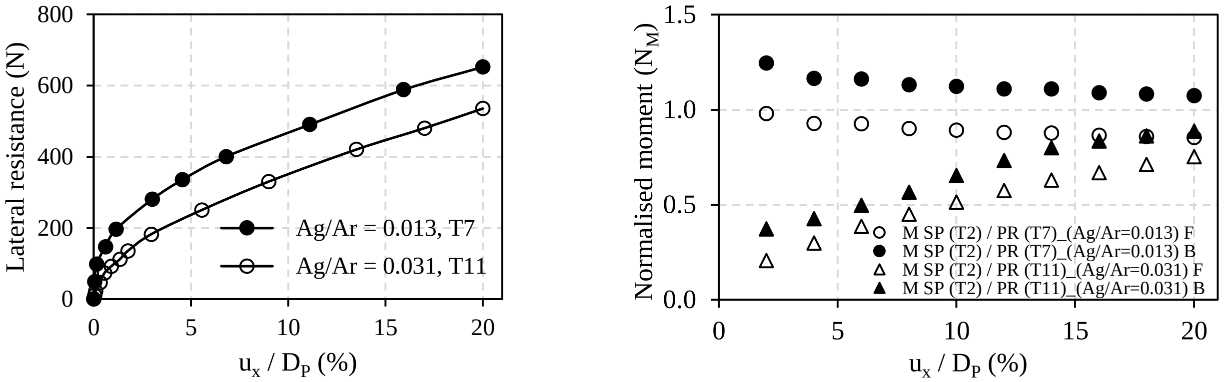
Fig. 10 Influence of slenderness ratio on lateral load sharing behavior of piled raft

increases in lateral load resistance varies in the range of 23–34% and 20–23% for u_x/D_P = 0 to 8% and 8 to 20% respectively. The lateral resistance carried by the pile group is 1.1–7% lower than the cumulative lateral resistance of four single piles. Fig. 8(b) shows that N_M initially increases gradually for u_x/D_P = 0–4% in the range of 0.90–1.0 and 3.10–3.60 in front and back piles of pile group respectively and increases gently for u_x/D_P = 4–20%. A similar trend has been observed in piles of piled raft foundations. The N_M initially increases gradually for u_x/D_P = 0–4% in the range of 0.70–0.95 and 2.60–2.90 in front and back piles of pile group respectively and increases gently in the range of u_x/D_P = 4–20%.

Fig. 9 shows that the lateral resistance of piled raft increases in the range of 14–20% and 20–25% for u_x/D_P = 0 to 8% and 8% to 20% with increasing the pile length from 500 mm (L_p/D_p = 25) to 1000 mm (L_p/D_p = 50). The increase in the lateral resistance of the foundation with increasing pile length is attributed due to the increase in the passive resistance offered by the piles with increasing pile length (Prasad and Chari 1999, Wang *et al*. 2023). Fig. 10 shows that the load sharing between pile and raft varies nonlinearly up to u_x/D_P = 4%. The pile load sharing increases in the range of 53–68% (L_p/D_p = 25) and 58–74% (L_p/D_p = 50) for u_x/D_P = 1–4%. The pile load sharing has been observed to be greater than the raft load sharing for u_x/D_P = 1–3% and varies in the range of 48–67%. The pile load sharing becomes nearly constant beyond u_x/D_P = 4% and varies in the range of 62–70%. The pile load sharing increases in the range of 11–15%, and 8–20% for u_x/D_P = 1–4%, and 4–20% respectively with increasing L_p/D_p from 25 to 50.

3.3 Effect of Ag/Ar

The influence of group area ratio on the behavior of laterally loaded piled raft has been evaluated by considering two different A_g/A_r by varying raft dimensions (Raft = 200 mm x 200 mm for A_g/A_r = 0.031 and Raft = 300 mm x 300 mm for A_g/A_r = 0.013) and keeping the pile geometry and number of piles same in both the cases. Fig. 11(a) shows that the large raft (A_g/A_r = 0.013) dimension contributes to relatively higher resistance in comparison with the smaller raft (A_g/A_r = 0.031) against the applied lateral load. The raft contact area with ground surfaces increases with an increase in the raft dimension. The lateral resistance increases in the range of 29–36% and 18–25% for u_x/D_P = 0 to 8% and 8 to 20% respectively. Fig. 11(b) shows that N_M initially increases rapidly for u_x/D_P = 0–10 % in the range of 0.20–0.60 and 0.40–0.70 in the front and back piles of pile group



(a) (b)

Fig. 11 Effect of Ag/Ar: (a) load settlement responses and (b) normalisd moment distribution in front and back pile in PG and PR

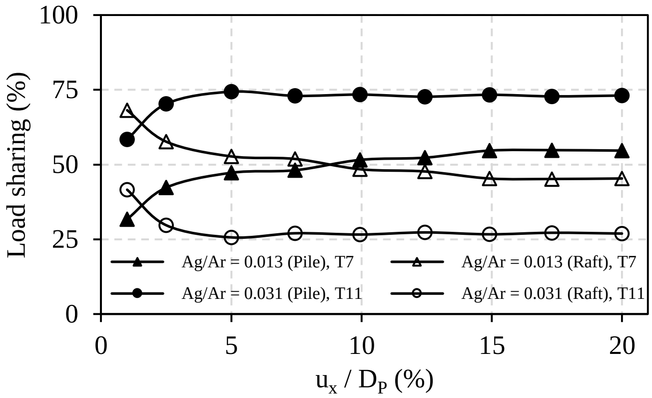
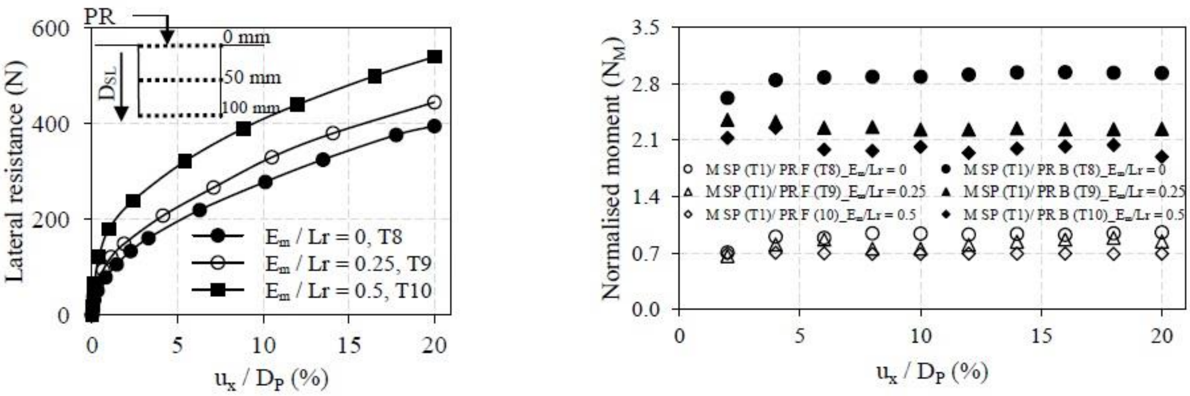


Fig. 12 Influence of A_g/A_r on lateral load sharing behavior of piled raft



(a) (b)

Fig. 13 Effect of embedment (L_P = 500 mm): (a) load settlement responses and (b) normalized moment distribution in front and back pile in foundations at different embedment

respectively and increases insignificantly for u_x/D_P in the range of 10–20%. A similar trend has been observed in piles of piled raft foundation, the N_M initially increases gradually for u_x/D_P = 0–6% in the range of 0.90–0.95 and 1.10–1.20 in front and back piles of pile group respectively and increases gently for u_x/D_P = 6–20%.

Fig. 12 shows that for u_x/D_P = 0–2%, the raft load share increases nonlinearly and varies in the range of 40–65%. The pile load sharing increases for u_x/D_P = 2–8% and caries in the range of 35–55%. The raft load share increases in the range 38–43%, 22–35%, and 22–24% for u_x/D_P = 0–2%, 2–8%, and 8–20% respectively with decreasing A_g/A_r from 0.031 to 0.013. The larger raft with A_g/A_r = 0.013 provides higher resistance attributing greater raft share in the overall lateral resistance of the piled raft in comparison to the piled raft with smaller raft having A_g/A_r = 0.031.

3.4 Effect of raft embedment

The influence of raft embedment on the responses of piled raft foundation has been evaluated by comparing the responses of the piled raft at the ground surface (E_m/L_r = 0),

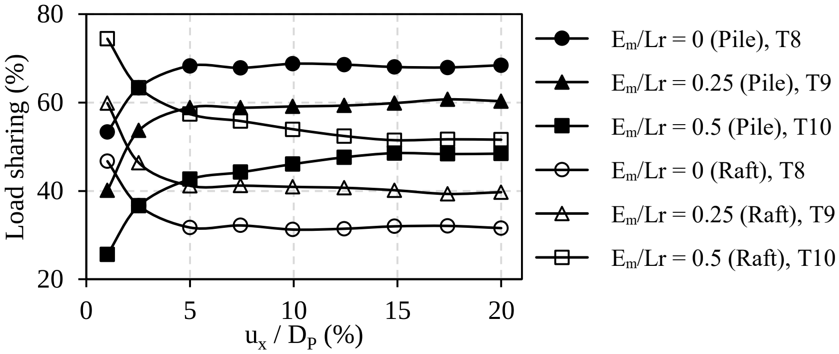


Fig. 14 Influence of Foundation embedment (L_P = 500 mm) on lateral load sharing behavior of piled raft

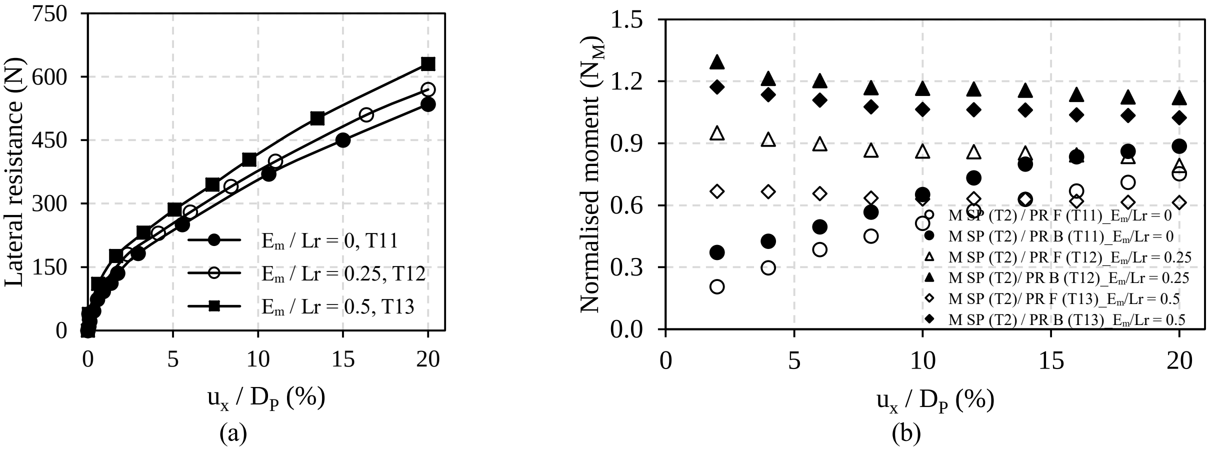


Fig. 15 Effect of embedment (L_P = 1000 mm): (a) load settlement responses and (b) normalisd moment distribution in front and back pile in foundations at different embedment

at 50 mm (E_m/L_r = 0.25) and 100 mm (E_m/L_r = 0.5) embedment depth. Fig. 13(a) shows that the lateral resistance of the piled raft increases nonlinearly in the range of 10–15% and 27–35% for u_x/D_P = 0–20% when E_m/L_R varied from 0 to 0.25 and 0.5 respectively. A similar trend has been observed by Swasdi *et al.* (2024). The lateral resistance of the piled raft foundation has been contributed due to the combined lateral resistances of the pile and raft. The different components of lateral resistance of piled raft are as follows i.e., (i) the shear resistance at bottom of raft due to relative movement between raft–soil interface (ii) the passive resistance offered by the soil in front of raft, and (iii) the lateral resistance offered by the piles in the piled raft. All the three components of lateral resistance of piled raft increases with an increase in the overburden stress. The increase in the overburden stress increases the normal stress at raft–soil interface level, passive resistance in front of the raft and passive resistance for the piles resulting an increased lateral resistance of piled raft. Fig. 13(b) shows that the N_M initially increases for u_x/D_P = 0–8% in the range of 0.70–0.95, 0.65–0.85, and 0.60–0.65 in the front pile of E_m/L_r = 0, E_m/L_r = 0.25 and E_m/L_r = 0.5 respectively. The normalized bending moment increases in the range of 2.60–2.90, 2.30–2.40, and 2.10–2.30 in the back pile of E_m/L_r = 0, E_m/L_r = 0.25, and E_m/L_r = 0.5 respectively

Fig. 14 shows that the raft load share is higher than the pile load share and varies in the range of 45–50% and 50–70% up to u_x/D_P = 2% and 6% for E_m/L_r = 0.25 and 0.5 respectively. The pile load share is higher than the raft load share and varies in the range of 60–80%, 45–70%, and 30–55% for u_x/D_P = 2–7%, 1–6%, and 6–8 % for E_m/L_r = 0, 0.25 and 0.5 respectively. The load–sharing ratio became almost constant for u_x/D_P = 6–20% and varies in the range of 80–82%, 70–75%, and 55–60% for E_m/L_r = 0, 0.25, and 0.5 respectively. The results show that the raft share increases in the range of 2.10 to 2.75 times with increasing the embedment depth twice from E_m/L_r = 0.25 to 0.5. The raft load share increases in the range of 11–15% and 9–11% with increasing E_m/L_r from 0 to 0.25 and 24–32% and 22–24% with increasing E_m/L_r from 0 to 0.5 for u_x/D_P = 1–12% and 12–20% respectively.

Fig. 15(a) shows that the lateral resistance of the piled raft increases nonlinearly in the range of 5–9% and 14–19 % for u_x/D_P = 0–20% with varying E_m/L_r from 0 to 0.25 and 0.5 respectively. The results affirm that the foundation embedment provides additional resistance to the piled raft. The increase in lateral resistance with foundation embedment in a piled raft with longer piles is significantly lower as compared to a piled raft with smaller piles. The result shows that the lateral resistance of the piled raft increases with increasing the pile length from 500 mm to 1000 mm and varies in the range of 18–26%, 10–21%, and

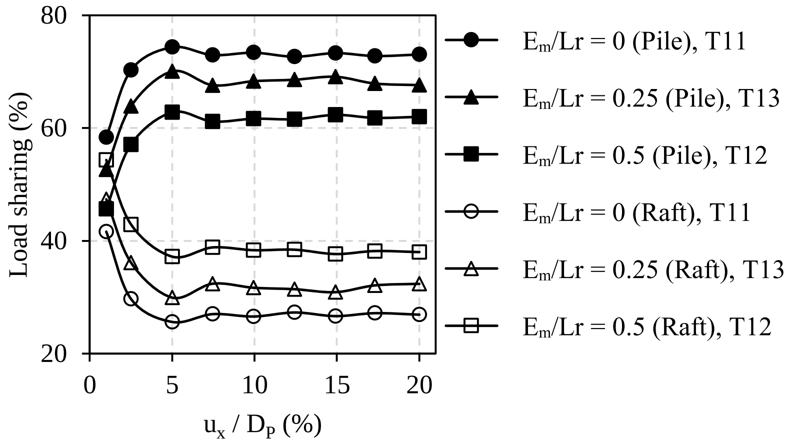


Fig. 16 Influence of foundation embedment (L_P = 1000mm) on lateral load sharing behavior of piled raft

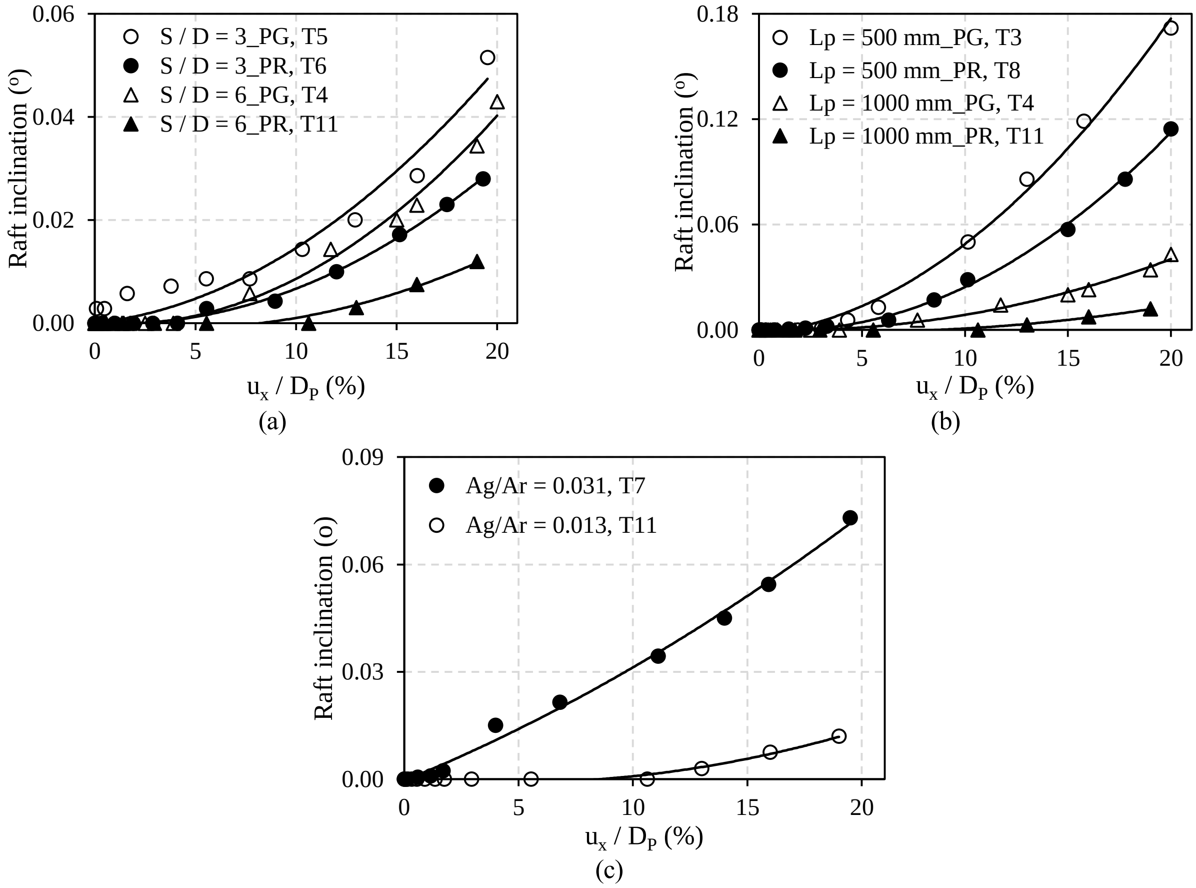
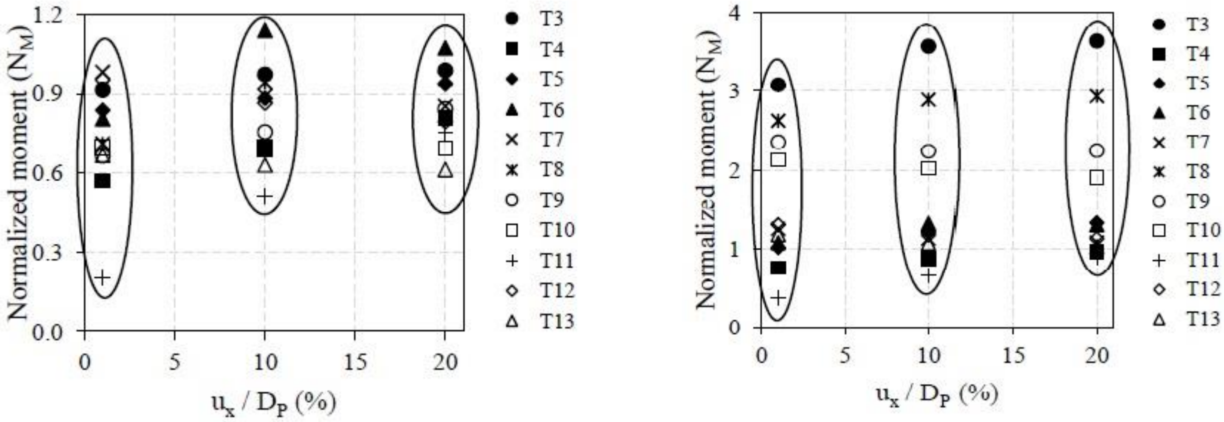


Fig. 17 Inclination of raft: (a) influence of pile spacing, (b) influence of pile length, and c) influence of group area ratio (A_g/A_r)

6–12% for E_m/L_r = 0, 0.25, and 0.5 respectively. The increase in the lateral resistance of the piled raft with increasing pile length is attributed to higher mobilization of passive resistance (Nasr 2014). Fig. 15(b) shows that the N_M increases for u_x/D_P = 0–10% in the range of 0.20–0.50, 0.90–1.0, and 0.60–0.70 in the front pile and 0.35–0.65, 1.20–1.30 and 1.02–1.15 in the back pile for E_m/L_r = 0, 0.25 and 0.5 respectively. Fig. 16 shows that the raft load share varies in the range of 38–48%, 48–54%, and 56–60% for u_x/D_P = 1–3% and for E_m/L_r = 0, 0.25 and 0.5 respectively. The pile load sharing varies in the range of 52–56%, 46–52%, and 41–48% in the range of u_x/D_P = 3–10% for E_m/L_r = 0, 0.25, and 0.5 respectively. The load–sharing ratio became almost constant for u_x/D_P = 10–20%, the pile load sharing varies in the range of 47–49%, 53–54%, and 56–58% for E_m/L_r = 0, 0.25, and 0.5 respectively. The result shows that the raft load share increases in the range of 2.10 to 2.75 times with increasing E_m/L_r = 0.25 to 0.5. The raft



(a) (b)

Fig. 18 Range of normalized moment in (a) front and (b) back pile in a pile group and piled raft foundation

load share increases in the range of 8–19% and 8–9% with increasing E_m/L_r from 0 to 0.5 for u_x/D_P = 1 to 12% and 12 to 20% respectively.

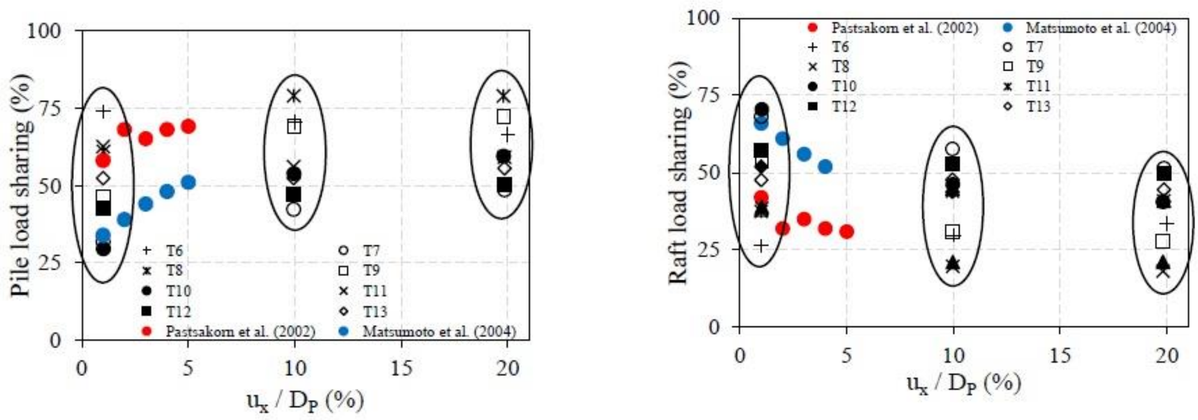
4. Raft inclination under lateral loading

Field investigations have shown that the raft inclination may eventually cause the superstructure to tilt and distort, which could eventually topple the structure (Charles and Skinner 2004). The understanding of the raft inclination will be useful in the safe design of the foundation. The inclination during lateral loading has not been explored by the researchers, however, it has been found that this characteristic of the foundation has a significant inference on the design of the foundation (Pastsakorn *et al*. 2002). The raft inclination in the range of 0.057° to 0.114° has been observed to be in permissible limits for a piled raft subjected to lateral loading (Matsumoto 2013). It has been observed from the limited laboratory investigations on model foundations and field investigation that the foundations subjected to lateral loading are prone to tilting (Mokwa and Duncan 2003). In the present study, an attempt has been made to compare the inclination in pile groups and piled rafts. Fig. 17(a) shows that the inclination in the pile group and piled raft increases in the range of 52–80% and 20–48% for u_x/D_P = 0 to 20% with reducing pile spacing from 6D to 3D respectively. The increases in pile spacing result in reduced overlapping of the influence zone of the individual pile which consequently increases the stiffness around the foundations (Yamashita *et al.* 2011). This stiffness results in reduced inclinations of the raft in the pile group and piled raft foundation. Fig. 17(b) shows that the raft inclination in the pile group and piled raft decreases in the range of 75–80% and 78–92% for u_x/D_P = 0 to 20% with increasing pile length from 500 mm to 1000 mm respectively.

The inclination decreases by 37–49% and 66–74% in a piled raft as compared to the pile group when pile length has been varied from 500 mm to 1000 mm respectively for u_x/D_p = 0–20%. The increase in pile length contributes to the higher shaft resistance of the pile consequently increasing the overall stiffness of the foundation system (Katzenbach *et al.* 2000). This stiffness results in reduced inclinations of the raft in the pile group and piled raft foundation. Fig. 17(c) shows that the inclination decreases 74–80% for u_x/D_P = 10–20% with varying A_g/A_r from 0.013 to 0.031. The result shows that the raft inclination is negligible up to u_x/D_P = 0 to 8% for A_g/A_r = 0.013. The reduced inclination of the piled raft in comparison to the similar pile group configuration shows the effectiveness of the raft in minimizing the raft inclination (Matsumoto *et al*. 2010). It has been concluded from the present observations that the raft inclination is negligible in the initial lateral loading stage i.e., for u_x/D_P = 1–3% which ensures its safety against the possible tilting within this lateral loading range (Pastsakorn *et al.* 2002), however the raft inclination gradually increases for u_x/D_P = 3–10% and varies increases abruptly beyond u_x/D_P = 10%.

5. Range of normalized moment and load sharing distribution in laterally loaded piled raft

The higher bending moment in the front pile in comparison to the back pile in both the pile group and piled raft foundations shows the higher passive resistance offered by the front piles. Fig. 18(a) summarizes the normalized bending moment in the front pile of the pile group and piled raft foundations. The N_M varies in the range of 0.2–1 for u_x/D_P = 1–2%. The N_M gradually increases and is observed to achieve the peak normalized bending moment in the range of 0.5–1.2 corresponding to u_x/D_P = 8–10%. The N_M is observed to be constant up to u_x/D_P = 10–20% with it's values varying in the range of 0.6–1.1. Fig. 18(b) summarizes the normalized bending moment in the back pile of the pile group and piled raft foundations. The N_M varies in the range of 0.4–3 for u_x/D_P = 1–2%. The N_M gradually increases and is observed to achieve the peak normalized bending moment in the range of 0.6–3.6 corresponding to u_x/D_P = 8–10%. The N_M is observed to be constant up to u_x/D_P = 10–20 % with it's values varying in the range of 0.8–3.6.



(a) (b)

Fig. 19 Range of load sharing of (a) pile and (b) raft in piled raft foundation

The comparison of the pile group and piled raft subjected to lateral loading affirms that the lateral resistance of the raft significantly contributes to the lateral load carrying capacity of the piled raft foundations. Fig. 19(a) summarizes the nonlinear lateral load sharing obtained from the present study considering different governing parameters. The pile load sharing varies in the range of 29–74% for u_x/D_P = 1–2%. The pile load sharing gradually increases and is observed to achieve the peak load sharing in the range of 42–79% corresponding to u_x/D_P = 8–10%. The pile load sharing is observed to be constant for u_x/D_P = 10–20% with the load sharing values varying in the range of 48–78%. Fig. 19(b) shows that the raft load sharing varies in the range of 26–71% for u_x/D_P = 1–2%. The raft load sharing gradually increases and varies in the range of 19–58% for u_x/D_P = 8–10%. The raft load sharing is observed to be nearly constant for u_x/D_P = 10–20% with variations in the range of 18–52%. The present study affirms that the raft significantly contributes in the overall lateral load resistance of the laterally loaded piled raft foundations. The lateral load sharing obtained from the wide range of parameters has been compared with some of the available lateral load sharing results obtained from 1 g testing (Pastsakorn *et al.* 2002) and centrifuge testing (Matsumoto *et al.* 2004) of laterally loaded piled raft foundations. Pastsakorn *et al.* (2002) used a pile of length 200 mm having a diameter of 20 mm with A_g/A_r = 0.0248. Matsumoto *et al.* (2004) used a pile of length 170 mm having a diameter of 10 mm with A_g/A_r = 0.0490. The comprehensive lateral load sharing attributing the influence of different governing parameters such as pile spacing, slenderness ratio, group area ratio, and embedment depth of the foundation will contribute to a more rational understanding of load sharing between pile and raft in laterally loaded piled raft foundations.

6. Conclusions

The present study compares the bearing behavior and flexural responses of the single pile, pile group, and piled raft foundation. Critical design parameters such as load sharing and raft inclination of the foudations have been discussed in detail. The following conclusions have been made based on the present study

1. The contribution of raft resistance in a piled raft foundation increases its lateral load resistance capacity by 28–49% in comparison to the pile group foundation with similar geometrical configurations in identical soil and loading conditions.
2. The bending moment in piles of a piled raft foundations are 45–50% and 85–90% lower than the piles in pile groups and single pile foundations respectively. The front pile in the pile group experiences 20–66% higher bending moment than the back piles whereas the front pile in the piled raft experiences 13–27% higher bending moment than the back piles.
3. The lateral resistance of piled raft increases in the range of 24–33%, 15–25%, and 18–36% with varying pile spacing from 3D to 6D, slenderness ratio from 25 to 50 and A_g/A_r from 0.031 to 0.013 respectively. The responses of the piled raft are significantly influenced by the foundation embedment. The lateral resistance increases in the range of 5–15% and 14–35% with varying E_m/L_r from 0 to 2.5 and 0.5 respectively.
4. The raft inclination in pile group foundations is higher than the piled raft foundations. The inclinations are negligible during initial lateral loading for u_x/D_p = 1–3% however it gradually increases for u_x/D_p = 8–10%.
5. The lateral pile load sharing sharply increases up to u_x/D_P = 2% and varies in the range of 25–75%, whereas it gently increases in the range of 50–75% for u_x/D_P = 2–7%. The pile load sharing becomes constant for u_x/D_P greater than 7%.

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Nomenclature

L_P – pile length
D_P – pile diameter
S_P – pile spacing
L_R – raft length
W_R – raft width
T_R – raft thickness
L_T – tank length
W_T – tank width
D_T – tank depth
L_B – lateral boundary
V_B – vertical boundary
q_c – cone tip resistance
u_x – foundation lateral displacement
A_g – pile group area in plan
A_r – raft area in plan
E_m – embedment depth
FT – foundation type
PR_L – lateral resistance of piled raft
ΣP_L – lateral resistance of piles
R_L – lateral resistance of raft
E_P – elastic modulus of the pile
I_P – moment of inertia of the pile
ε – strain
SP – single pile
PG – pile group
PR – piled raft
N_M – normalized moment
FP – front pile
BP – back pile
M SP – bending moment, single pile
PG F – bending moment, front pile (pile group)
PG B – bending moment, back pile (pile group)
PR F – bending moment, front pile (piled raft)
PR B – bending moment, back pile (piled raft)