

### **3 SCOPE, OBJECTIVES AND SCHEME OF INVESTIGATION**

#### **3.1 Need for Research in Piled Raft Foundation:**

The analysis and design procedures of piled raft foundations involve the use of sophisticated software based on numerical methods such as the finite element method, finite difference method, boundary element method, etc. These procedures consume a lot of computational effort and time. Some of the known software, like PLAXIS 2D and PLAXIS 3D, ABAQUS, FLAC 3D is widely used for this purpose. It is necessary to develop simple methods and procedures for the analysis and design of piled raft foundations. Burland (1977) and Randolph (1994) presented simplified methods in this regard. Poulos (2001) presented a philosophy for the analysis and design of piled raft foundations, which needs tremendous computational and numerical efforts. Hence, he emphasized the need for intensive research for the development of such an analytical procedure. Till today, there is no such codal provision in India that can be useful for the analysis and design of piled raft foundations.

Very limited research has been done on simplified analysis and design methods for piled raft foundations up till now. Conventional design procedures result in very conservative designs, and limited work has been done on the load-sharing capacity between pile and raft. Mendolini et al. (2005) show that load sharing between raft and pile is a fundamental quantity in advanced design methods. To develop simplified methods for predicting load sharing between piles and raft in a piled raft foundation, it will be useful to establish design guidelines in the codes and manuals of foundation structures. There is limited research reported on the load sharing of piled raft foundations, which incorporate various parameters from soil, pile, and raft. EL-Mossallamy et al. (2009) reported that simplified methods that are able to give a quick answer on the design criteria such as the number and length of piles, the pile load share, and the settlement of the piled raft foundation are highly recommended from a practical point of view. A limited study has been conducted for the effect of various parameters on load settlement characteristics of the piled-raft foundation and, from the study, to evaluate load sharing between the pile group and raft and the overall settlement of the system.

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### 3.2 Scope

The present investigation aims at a systematic study of load settlement characteristics of raft alone, pile group alone, and piled-raft systems through model experimental study along with partial numerical study to develop an analytical model for predicting the capacity of the piled-raft foundation along with load sharing mechanisms between pile group and raft and settlement by incorporating some important design parameters related to pile, raft, and soil with emphasis on pile-soil, raft-soil interaction.

### 3.3 Objectives

Following are the main objective of the study

#### 3.3.1 Objectives of Experimental Study

- To examine the effect of the following factors on unpiled raft load-settlement characteristics and contact pressure distribution beneath the raft:
  - Relative density of sand bed ( $I_d = 40\%$ ,  $60\%$  and  $80\%$ )
  - shape of raft with equal contact area (Square, Rectangular, Circular, Trapezoidal)
- To examine the effect of the following factors on Single pile load-settlement characteristics:
  - Relative density of sand bed ( $I_d = 40\%$ ,  $60\%$  and  $80\%$ )
  - length to diameter ratio of pile ( $L/d = 10, 20, 30$ )
  - cross-section shape of pile (H, hollow circular, hollow square)
- To examine the effect of the following factors on pile group load-settlement characteristics:
  - Relative density of sand bed ( $I_d = 40\%$ ,  $60\%$  and  $80\%$ )
  - length to diameter ratio of pile ( $L/d = 10, 20, 30$ )
  - spacing between piles ( $S = 3d, 5d,$  and  $7d$ )
  - cross-section shape of pile (H, hollow circular, hollow square)
- To examine the effect of the following factors on model piled raft load-settlement characteristics, and load sharing between pile group and raft:

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- Relative density of sand bed ( $I_d = 40\%$ ,  $60\%$  and  $80\%$ )
- Piled raft settlement
- spacing of piles ( $S = 3d$ ,  $5d$ , and  $7d$ )
- length to diameter ratio of pile ( $L/d = 10$ ,  $20$ ,  $30$ )
- configurations of piles (as described in article 4.1.5)
- soil-pile friction (as described in article 4.1.3)
- shape of raft (Square, Rectangular, Circular, Trapezoidal)
- shape of piles (H, hollow circular, hollow square)

### 3.3.2 Objectives of Numerical Study

- To justify few experimental results on piled raft with different configuration of piles and shape of raft.
- To verify the developments made in model experiments in a prototype piled raft foundation through numerical analysis.

## 3.4 Scheme of Investigation

Table 3-1 to Table 3-4 present the testing program followed in this study. The experimental tests were divided into four main series; the tests on Model Unpiled raft foundation (UPR) (Table 3-1), Model single pile foundation (SP) (Table 3-2), Model pile group foundation (PG) (Table 3-3), and Model piled raft foundation (PRF) (Table 3-4). Each series consists of 3 tests, which were conducted on different densities of sand bed. For validation of experimental results, some test results were simulated in PLAXIS 3D software as per the details given in Table 3-5.

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Table 3-1 Test on Model Unpiled raft foundation

Variables of the study	Shape of unpiled raft	$I_d$	MRFD	N
Shape of raft and relative density of sand bed	Square (SQ)	40%,60%,and 80% (OS)	220 mm × 220 mm × 25 mm	3
	Rectangular (RECT)	40%,60%,and 80% (OS)	240 mm × 180 mm × 230 mm ×25 mm	3
	Trapezoidal (TRAP)	40%,60%,and 80% (OS)	260 mm ×186.1 mm × 25 mm	3
	Circular (CIR)	40%,60%,and 80% (OS)	248.24 mm diameter	3
Shape of pile and relative density of sand bed	Square (SQ)	40%,60%,and 80% (NS)	240 mm × 240 mm × 25 mm	3
<b>Total</b>				<b>15</b>

$I_d$  = relative density of sand bed; N = Number of experiments; MRFD = Model raft dimensions; OS = Orsang river sand; NS= Narmada river sand; SQ = square shaped raft; RECT= rectangular shaped raft; TRAP = Trapezoidal shaped raft; CIR = circular shaped raft

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Table 3-2 Test on Model single pile foundation

Variables of the study		$d$ or CSD(mm)	$L$ (mm)	$L_t$ (mm)	$I_d$	N
$L/d$ ratio of pile and relative density of sand bed	10	$d = 9.7; d_i = 7.8$	97	157	40%,60%,and 80% (OS)	3
	20	$d = 9.7; d_i = 7.8$	194	254	40%,60%,and 80% (OS)	3
	30	$d = 9.7; d_i = 7.8$	291	351	40%,60%,and 80% (OS)	3
<b>Total</b>						09

$I_d$ = relative density of sand bed;  $d$  = external diameter of pile;  $d_i$ = Internal diameter of pile;  $L/d$  = ratio of Embedded length of pile to external diameter of pile;  $L_t$  = Total length of pile;  $L$  = Embedded length of pile; N = Number of experiments; OS= Orsang river sand

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Table 3-3 Test on Model pile group foundation

Variables of the study		$I_d$	$d$ or CSD(mm)	$L$ (mm)	$L_t$ (mm)	PG	$S$	$N$
L/d ratio of pile and relative density of sand bed	$L/d = 10$	40%,60%,and 80% (OS)	$d = 9.7; d_i = 7.8$	97	157	$5 \times 5$	$5d$	3
	$L/d = 20$	40%,60%,and 80% (OS)	$d = 9.7; d_i = 7.8$	194	254	$5 \times 5$	$5d$	3
	$L/d = 30$	40%,60%,and 80% (OS)	$d = 9.7; d_i = 7.8$	291	351	$5 \times 5$	$5d$	3
Shape of pile and relative density of sand bed	H	40%,60%,and 80% (NS)	$FW = 15; WH = 14; FT = 2; WT = 2$	300	360	$3 \times 3$	$5d$	3
	HC	40%,60%,and 80% (NS)	$d = 16; d_i = 12$	300	360	$3 \times 3$	$5d$	3
	HSQ	40%,60%,and 80% (NS)	$B = 16; t = 1.5$	300	360	$3 \times 3$	$5d$	3
Spacing of pile and relative density of sand bed	$S=3d$	40%,60%,and 80% (OS)	$d = 9.7; d_i = 7.8$	291	351	$3 \times 3$	$3d$	3
	$S=5d$	40%,60%,and 80% (OS)	$d = 9.7; d_i = 7.8$	291	351	$3 \times 3$	$5d$	3
	$S=7d$	40%,60%,and 80% (OS)	$d = 9.7; d_i = 7.8$	291	351	$3 \times 3$	$7d$	3
Total								27

PG = pile group;  $I_d$  = relative density of sand bed;  $d$  = external diameter of pile;  $L/d$  = ratio of Embedded length of pile to external diameter of pile;  $L_t$  = Total length of pile;  $L$  = Embedded length of pile;  $S$  = center to center spacing between piles;  $N$  = Number of experiments; OS = Orsang river sand; NS = Narmada river sand; H = H shape of pile; HC = Hollow Circular shape of pile; HSQ = Hollow square shape of pile; CSD = Cross-section dimensions of pile;  $FW$  = Flange Width;  $WH$  = Web height;  $FT$  = Flange thickness;  $WT$  = Web thickness;  $B$  = Width of hollow square pile;  $t$  = thickness of hollow square pile;  $d_i$  = Internal diameter of pile

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Table 3-4 Test on Model piled raft foundation

Variables of the study	$L/d$	$I_d$	$d$ or $CSD(mm)$	$L$ (mm)	$L_r$ (mm)	PG	$S$	MRFD	N	
$L/d$ ratio of pile and relative density of sand bed	$L/d = 10$	40%,60%,and80% (OS)	$d=9.7; d_i=7.8$	97	107	5 x 5	5d	220mm x 220mm x 25mm	3	
	$L/d = 20$						5d	220mm x 220mm x 25mm	3	
	$L/d = 30$						5d	220mm x 220mm x 25mm	3	
Shape of pile and relative density of sand bed	H	40%,60%,and80% (NS)	$FW=15; WH=14; FT=2; WT=2$	300	310	3 x 3	5d	240mm x 240mm x 25mm	3	
	HC						5d	240mm x 240mm x 25mm	3	
	HSQ						5d	240mm x 240mm x 25mm	3	
Spacing of pile and relative density of sand bed	$S=3d$	40%,60%,and80% (OS)	$d=9.7; d_i=7.8$	291	301	3 x 3	3d	220mm x 220mm x 25mm	3	
	$S=5d$						5d	220mm x 220mm x 25mm	3	
	$S=7d$						7d	220mm x 220mm x 25mm	3	
Shape of raft and relative density of sand bed	SQ	40%,60%,and80% (OS)	$d=9.7; d_i=7.8$	291	301	3 x 3	7d	220mm x 220mm x 25mm	3	
	TRAP						7d	240mm x 180mm x 230mm x 25mm	3	
	RECT						7d	260mm x 186.1mm x 25mm	3	
Configuration of piles	CF-1 to CF-9 (section 4.1.5)	40%,60%,and80% (OS)	$d=9.7; d_i=7.8$	291	301	3 x 3	7d	248.24 mm diameter	3	
							$\delta_0$ to $\delta_3$ (Table 4-4)	5d	220mm x 220mm x 25mm	9
Soil-pile friction angle ( $\delta$ ) and relative density of sand bed	$\delta_0$ to $\delta_3$ (Table 4-4)	40%,60%,and80% (OS)	$d=9.7; d_i=7.8$	291	301	3 x 3	5d	220mm x 220mm x 25mm	12	
Total									60	

PG = pile group;  $I_d$  = relative density of sand bed;  $d$  = external diameter of pile;  $L/d$  = ratio of Embedded length of pile to external diameter of pile;  $L_r$  = Total length of pile;  $L$  = Embedded length of pile;  $S$  = center to center spacing between piles; N = Number of experiments; MRFD = Model raft dimensions; OS = Orsang river sand; NS = Narmada river sand;  $H$  = H shape of pile; HC = Hollow Circular shape of pile; HSQ = Hollow square shape of pile;  $CSD$  = Cross-section dimensions of pile;  $FW$  = Flange Width;  $WH$  = Web height;  $FT$  = Flange thickness;  $WT$  = Web thickness;  $B$  = Width of hollow square pile;  $t$  = thickness of hollow square pile;  $d_i$  = Internal diameter of pile; SQ = square shaped raft; RECT = rectangular shaped raft; TRAP = Trapezoidal shaped raft; CIR = circular shaped raft

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Table 3-5 Numerical study on Model piled raft foundation

Variables of the study	Pattern of configuration of piles	$d$ or $CSD$	$L$	PG	$S$	RFD	$I_d$	N
Spacing of piles	square piled raft with 9 piles in square group	$d = 9.7$ mm; $d_i = 7.8$ mm	291 mm	3 × 3	$7d$	220 mm × 220 mm × 25 mm	60%	1
$L/d$ ratio of pile	CF-7	$d = 9.7$ mm; $d_i = 7.8$ mm	194 mm	5 × 5	$5d$	220 mm × 220 mm × 25 mm	60%	1
Configuration of piles	Various Configuration of pile in square pattern (S1 – S9) (Figure 4-47)	$d = 0.6$ m	6 m, 12 m, 18 m	5 × 5	$5d$	13.608 m × 13.608 m × 1.5 m	60%	9
	Various Configuration of pile in circular pattern (C1- C9) (Figure 4-47)	$d = 0.6$ m	6 m, 12 m, 18 m	5 × 5	$5d$	13.608 m × 13.608 m × 1.5 m	60%	9
<b>Total</b>								20

### 3.5 Materials of Investigation

#### 3.5.1 Soil

Clean air dried silica sand was used as the foundation soil in this study. The commercially available Orsang river sand (OS) near Badarpur and Narmada river sand (NS) near Poicha were used as a foundation soil. The particle size distribution curves of both these sands are shown in Figure 3-1. As per the IS classification both are fall in the category of poorly graded sand. The Index Properties and shear strength properties of both types of sands are as listed in Table 3-6. Microscopic pictures of sand particles are shown in Figure 3-2.

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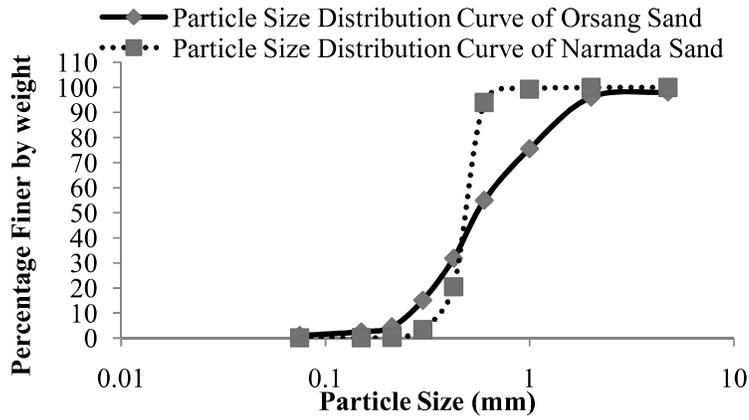


Figure 3-1: Particle Size Distribution Curve of Orsang River Sand and Narmada River Sand (Dry Sieve Analysis Test)

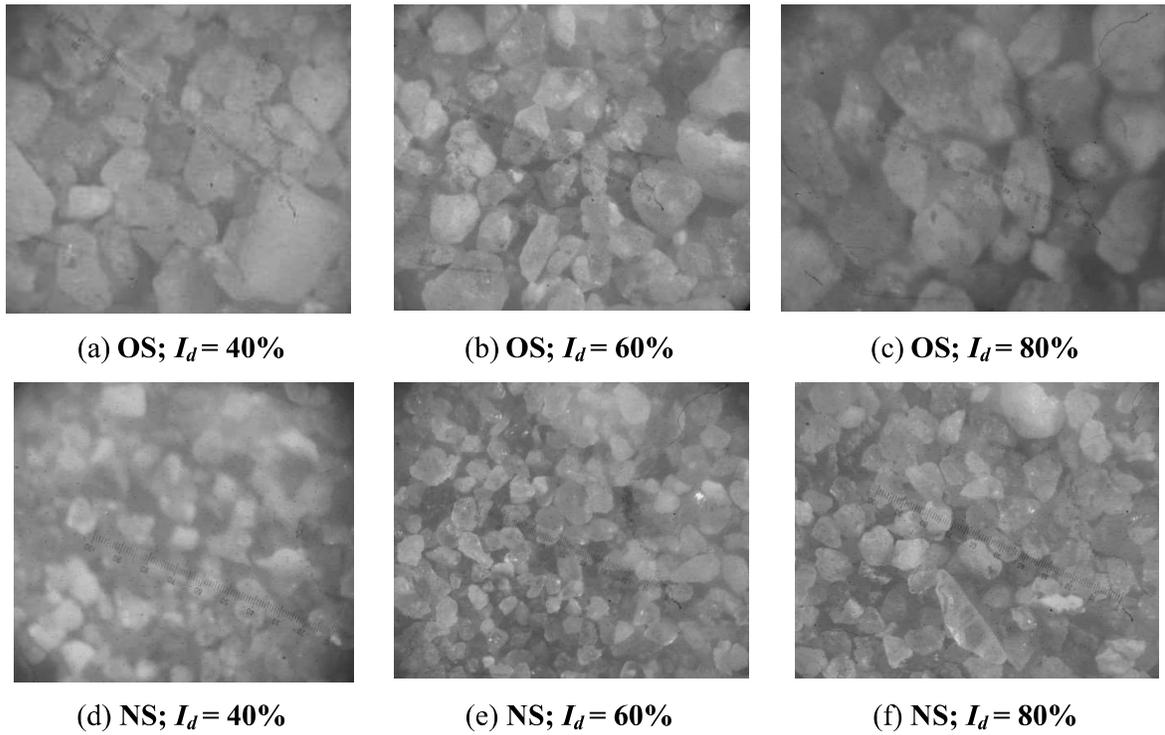


Figure 3-2 : Microscopic view of sand particles with 10 x magnification

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Table 3-6 Index and Engineering properties of sand

Sr. No.	Property	Unit	Values for Orsang river Sand	Values for Narmada river sand
1.	Specific Gravity	-	2.63	2.62
2.	$D_{10}$	mm	0.26	0.35
	$D_{30}$	mm	0.41	0.45
	$D_{60}$	mm	0.7	0.52
3.	Coefficient of Uniformity ( $C_u$ )	-	2.711	1.49
4.	Coefficient of Curvature ( $C_c$ )	-	0.94	1.108
5.	Classification of sand (IS Classification)	-	SP- poorly graded sand	SP- Uniformly graded sand
6.	Maximum Density	(kN/m <sup>3</sup> )	18.3	16.7
7.	Minimum Density	(kN/m <sup>3</sup> )	15.0	14.3
8.	Density of sand at 40% Relative Density ( $I_d = 40\%$ )	(kN/m <sup>3</sup> )	16.2	15.2
9.	Density of sand at 60% Relative Density ( $I_d = 60\%$ )	(kN/m <sup>3</sup> )	16.8	15.7
10.	Density of sand at 80% Relative Density ( $I_d = 80\%$ )	(kN/m <sup>3</sup> )	17.5	16.2
11.	Angle of internal friction at $I_d = 40\%$ (from Direct shear box test)	degree	32	30
12.	Angle of internal friction at $I_d = 60\%$ (from Direct shear box test)	degree	35	32
13.	Angle of internal friction at $I_d = 80\%$ (from Direct shear box test)	degree	39	35
14.	Cohesion (at 40%, 60% and 80% $I_d$ )	kPa	00	00
15.	Modulus of Elasticity of Sand Es at $I_d = 40\%$ (from Triaxial test)	kPa	21667	13879
16.	Modulus of Elasticity of Sand Es at $I_d = 60\%$ (from Triaxial test)	kPa	33889	20952
17.	Modulus of Elasticity of Sand Es at $I_d = 80\%$ (from Triaxial test)	kPa	39167	25229
18.	Modulus of Subgrade Reaction $k_s$ at $I_d = 40\%$ (from Plate Load test)	kN/m <sup>2</sup> /m	49219	26250
19.	Modulus of Subgrade Reaction $k_s$ at $I_d = 60\%$ (from Plate Load test)	kN/m <sup>2</sup> /m	87500	56250
20.	Modulus of Subgrade Reaction $k_s$ at $I_d = 80\%$ (from Plate Load test)	kN/m <sup>2</sup> /m	112500	65625
21.	Poisson's ratio at $I_d = 40\%$	-	0.313	0.3
22.	Poisson's ratio at $I_d = 60\%$	-	0.28	0.25
23.	Poisson's ratio at $I_d = 80\%$	-	0.259	0.2

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### 3.5.2 Material used for Model Pile and Raft

The model pile/ pile groups and raft were fabricated from Mild steel of grade  $f_y = 250$  MPa. Mild steel plates were used to prepare the model rigid rafts and mild Steel rods with hollow circular cross section were used to prepare the model piles. The unit weight and Young's modulus of the mild steel were  $78.5 \text{ kN/m}^3$  and  $2.1 \times 10^8 \text{ kN/m}^2$  respectively. The tensile yield load and ultimate load of hollow pile was found to be 3.5 kN and 7 kN respectively. Further description is given in chapter 4.