CHAPTER 3

EXPERIMENTAL PROGRAMME

3.1 INTRODUCTION

The critical review of the literature presented in the previous chapter reveals the limitations of the experimental studies carried out so far in the field and laboratory to investigate the lateral response of single piles and pile groups. Hence, in the present study, a comprehensive experimental investigation has been undertaken to understand the response of single piles and pile groups in sand, gravelly sand and clay under static lateral loads. This chapter describes the details of materials used, scaling law adopted to select the model pile and the experimental setup. The soil bed preparation and test procedures adopted in the present study are also discussed. Finally the scheme of test programme comprising of several series of experiments is given at the end.

3.2 PROPERTIES OF SOIL

Static lateral load tests are conducted on piles embedded in (a) sand, (b) gravelly sand and (c) clay. The properties of soil are presented in the following section.

3.2.1 SAND

Sand collected from Palar river in Vellore, India is used in the present study. Sieve analysis, relative density test and specific gravity test are carried out as per relevant ASTM standards. Grain size distribution curve of the soil is shown in Figure 3.1. Properties of sand are: Specific gravity (G) = 2.64, Coefficient of uniformity (c_u) = 4, Coefficient of curvature (c_c) = 1.02, Minimum dry density (ρ_d(min)) = 1528 kg/m^3, Maximum dry density (ρ_d(max)) = 1816 kg/m^3, Minimum void ratio (e_min) = 0.45 and Maximum void ratio (e_max) = 0.73. Soil is classified as poorly graded sand (SP) as per Unified Soil Classification System (USCS) (ASTM D2487–11).
3.2.2 GRAVELLY SAND

Static lateral load tests on piles embedded in gravelly sand are carried out by taking field test conducted at Provo, USA as the referred field test. The referred field tests consist of lateral load tests on full-scale steel piles embedded in gravelly sand in Mechanically Stabilised Earth (MSE) wall (Han 2014, Hatch 2014, Rollins 2015) as showing Fig. 3.2.
The granular soil collected from Cheyyar crusher in Thiruvannamalai district, Tamil Nadu, India is used in this study. Sieve analysis, Specific gravity, Modified Proctor compaction test and Direct shear (Unconfined Undrained) test are conducted on the soil samples. Grain size distribution curve of the soil is shown in Fig. 3.3.
The soil is classified as poorly graded sand (SP) according to USCS (ASTM D 2487-11) and as gravelly sand (A-1-a) according to AASHTO classification. As can be seen from the Fig. 3.2, the grain size distribution of the curve of the soil used in lab tests on model piles matches well with that of the backfill used in the field tests on full-scale piles. The soil used in the field tests has more fines content. Properties of the soil used in the model test and backfill used in the field test are presented in Table 3.1. Grain size distribution, maximum dry density, angle of internal friction of the soil in the model test match very well with the properties of the soil used as backfill in field tests.

![Grain size distribution of gravelly sand](image.png)

**Fig. 3.3 Grain size distribution of gravelly sand**
Table 3.1 Properties of gravelly sand

<table>
<thead>
<tr>
<th>S.No</th>
<th>Properties of soil</th>
<th>Soil used in the model test</th>
<th>Backfill used in referred field test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Specific gravity (G)</td>
<td>2.63</td>
<td>2.65</td>
</tr>
<tr>
<td>2</td>
<td>Maximum dry unit weight ($\gamma_{\text{dmax}}$) kN/m$^3$</td>
<td>19.5</td>
<td>20.5</td>
</tr>
<tr>
<td>3</td>
<td>Optimum moisture content (OMC) %</td>
<td>4.5</td>
<td>7.8</td>
</tr>
<tr>
<td>4</td>
<td>Coefficient of uniformity ($C_u$)</td>
<td>4.1</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>Coefficient of curvature ($C_c$)</td>
<td>1</td>
<td>2.4</td>
</tr>
<tr>
<td>6</td>
<td>Angle of internal friction ($\phi$) (Degree)</td>
<td>34.20</td>
<td>34</td>
</tr>
<tr>
<td>7</td>
<td>Classification of soil (USCS) (Unified Soil Classification System)</td>
<td>Poorly graded Sand (SP)</td>
<td>SW - SM</td>
</tr>
<tr>
<td>8</td>
<td>Classification of soil (AASHTO)</td>
<td>Gravelly sand A-1-a</td>
<td>Gravelly sand A-1-a</td>
</tr>
</tbody>
</table>

3.2.3 CLAY

Clay samples collected from Kanchipuram near Vellore in Tamilnadu state of India is used in the present study. The properties of the clay are: liquid limit = 53%, plastic limit = 24%, plasticity index= 29% and undrained shear strength at soft consistency (consistency index of 0.32) = 8kPa. As per Unified Soil Classification System, the soil is classified as fat clay (CH) (ASTM D2487 - 11 2011). The percentage of the clay content is 46 % and silt content is 54 %.
3.3 MODEL PILE

In the present experimental investigations, model pile material and its dimensions are selected adhering to the following similitude law proposed by Wood et al (2002).

\[
\frac{E_m I_m}{E_p I_p} = \frac{1}{n^{\alpha+4}}
\]  

(3.1)

Where \(E_m\) = modulus of elasticity of model pile, \(I_m\) = moment of inertia of model pile, \(E_p\) = modulus of elasticity of prototype pile, \(I_p\) = moment of inertia of prototype pile, \(1/n\) = scale factor for length, \(\alpha\) = exponent (\(\alpha = 0.5\) for sand and gravelly sand, 1 for clay)

For tests in sand, model pile of polyvinylchloride (PVC) pipe with outer diameter of 32mm and inner diameter of 27 mm was selected as model pile with a length scaling factor of 1/25. This is used to simulate the prototype pile of 600 mm diameter solid section made of reinforced cement concrete with a compressive strength of 30 N/mm\(^2\) (IS456-2000). Plywood sheets of 17 mm thick were used as pile caps. The pile cap was attached at the top of piles with a free standing length of 160 mm above the ground surface. The piles are inserted in the pile caps to get a free head condition.

For tests in gravelly sand, the above scaling law is used to model the field full-scale steel pipe pile (diameter of 324 mm and wall thickness 9 mm) used in the field tests conducted at test site at Provo, USA (Fig.3.2b). Scaling factors adopted is presented in Table 3.2. Three types of model piles made of aluminium, steel and polyvinyl chloride (PVC) are selected. The properties of model piles and field piles are mentioned in Table 3.3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Scaling factors for 1g modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1/n</td>
</tr>
<tr>
<td>Density</td>
<td>1</td>
</tr>
<tr>
<td>Pile flexural rigidity</td>
<td>(1/n^{\alpha+4})</td>
</tr>
<tr>
<td>Force</td>
<td>(1/n^3)</td>
</tr>
</tbody>
</table>

The details of selection of pile materials and properties
Model pile material and its dimension are selected based on the similitude law (Wood et al 2002) (Scaling law), $E_m I_m / E_p I_p = 1/n^{4+\alpha}$

**PVC**: $E_p x I_p / E_m x I_m = n^{4.5} = 2x10^5 \times 1.16x10^8 / 2758 \times 25384.8 = n^{4.5} = n = 16.8$

**Aluminium**: $E_p x I_p / E_m x I_m = n^{4.5} = 2x10^5 \times 1.16x10^8 / 70x10^3 \times 13472 = n^{4.5} = n = 9.4$

**Steel**: $E_p x I_p / E_m x I_m = n^{4.5} = 1 \times 1.16x10^8 / 1 \times 13472 = n^{4.5} = n = 7.4$

Table 3.3 Properties of model piles used in gravelly sand and referred field piles

<table>
<thead>
<tr>
<th>Model pile</th>
<th>Dimensions (mm)</th>
<th>Embedment length of model pile (mm)</th>
<th>Moment of Inertia (model pile) $I_m$ (mm$^4$)</th>
<th>Young’s Modulus (model pile) $E_m$ (N/mm$^2$)</th>
<th>Moment of Inertia (field pile) $I_p$ (mm$^4$)</th>
<th>Young’s Modulus (field pile) $E_p$ (N/mm$^2$)</th>
<th>Scaling factor for length (1/n)</th>
<th>Length to Diameter ratio (L/D) (model pile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>OD = 25.40 ID = 19.40 Wall thickness $t = 3$ mm</td>
<td>810</td>
<td>13472</td>
<td>$70x10^5$</td>
<td>$1.16x10^8$</td>
<td>$2x10^5$</td>
<td>10</td>
<td>32</td>
</tr>
<tr>
<td>Steel pile</td>
<td>OD = 25.40 ID = 19.40 Wall thickness $t = 3$ mm</td>
<td>810</td>
<td>13472</td>
<td>$2x10^5$</td>
<td>$1.16x10^8$</td>
<td>$1.16x10^8$</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>PVC (Polyvinyl chloride)</td>
<td>OD = 32mm ID = 26.8mm Wall Thickness $t = 2.6$ mm</td>
<td>810</td>
<td>25385</td>
<td>$2.61x10^4$</td>
<td>$2x10^5$</td>
<td>17</td>
<td>26</td>
<td></td>
</tr>
</tbody>
</table>

For tests in clay, model pile made of aluminium (tube having outer diameter of 19.6 mm, wall thickness of 1.2 mm and internal diameter of 17.2 mm) with a length scaling factor of 1/10 is used. This simulates a prototype pile of 350 mm diameter solid section made of reinforced cement concrete having compressive strength of 30 N/mm$^2$ (IS 456-2000).
3.4 CONFIGURATION OF PILE GROUPS

Configuration of different pile groups for tests in sand, gravelly sand and clay are shown in Fig. 3.4, 3.5, 3.6 respectively.

Fig. 3.4 Configuration of pile groups for tests in sand

Fig. 3.5 Configuration of pile groups for tests in gravelly sand
Fig. 3.6 Configuration of pile groups for tests in clay: (a) 1 × 2 group, (b) 2 × 2 group, (c) 3 × 3 group and (d) 3 × 4 group
3.5 EXPERIMENTAL SETUP, PROCEDURE AND TEST PROGRAMME

The schematic diagram of the lateral load test setup is shown in Figure 3.7. Tests are conducted on model piles embedded in soil in a rectangular steel testing chamber of 1 m length, 0.6 m breadth and 1 m height. This is sufficiently large enough to avoid boundary effects.

(a) Over all view
3.5.1 LATERAL LOAD TESTS ON PILES EMBEDDED IN SAND

In lateral load tests in sand, the dry density ($\rho_d$) of sand was calculated using the following expression for a given relative density,

$$D_r = \frac{\rho_{d\max}}{\rho_d} \times \frac{(\rho_d - \rho_{d\min})}{(\rho_{d\max} - \rho_{d\min})} \quad (3.2)$$

The tank chamber is divided into five layers of each 20 cm thickness. The mass of dry sand to be filled in each layer was calculated. Model piles along with pile caps are placed in position using templates in the testing chamber. The bottom end of model pile is closed with a PVC plug. The required quantity of dry sand was filled in each layer using sand raining technique (Gandhi and Selvam 1997). Static lateral load is applied on the model piles by placing dead weights on a hanger connected to a flexible steel rope strung over a

Fig. 3.7 Experimental setup (a) Over all view and (b) Schematic diagram
pulley supported by the loading frame as shown in Figure 3.7. The loads are applied in increments and are maintained for a period of 30 minutes to allow the deflection to stabilize. Deflection of pile cap is measured using deflectometer. Static lateral load tests are conducted on model single piles and pile groups embedded in dry sand with relative densities of 30% and 50%.

For relative density of 30%, tests are conducted in the following sequence:

1. Single pile with length to diameter (L/D) ratio of 12, 20 and 26

2. 1 × 2 and 2 × 2 pile groups with L/D ratio of 20 and spacing (in the direction of loading) to diameter (S/D) ratio of 3, 5 and 7.

3. 2 × 3 pile group with L/D ratio of 20 and S/D ratio of 3.

For relative density of 50%, tests are conducted in the following sequence:


2. 1 × 2, 2 × 2 pile groups with L/D ratio of 20 and S/D ratio of 3.

The spacing in the direction perpendicular to the direction of loading (S_T) was kept constant as 3D for 2 × 2 and 2 × 3 pile groups.

The piles are classified as rigid or flexible based on the stiffness factor (T) (Matlock and Reese 1960, Broms 1964, Chae et al. 2004)

\[
\text{Stiffness factor } T = \left( \frac{EI}{n_h} \right)^{0.2} \tag{3.3}
\]

where EI = bending stiffness of pile and n_h = coefficient of modulus variation. The n_h values of 6500 kN/m^3 and 15000 kN/m^3 are adopted for relative density (D_r) 30% and 50% respectively as recommended by Reese et al. (1974) based on field lateral tests on instrumented piles. The piles are said to be rigid if the length of the pile is less than 2T and flexible if the length of the pile is greater than 4T. For D_r = 30% and 50%, piles with L/D of 20 are in flexible range.
3.5.2 LATERAL LOAD TESTS ON PILES EMBEDDED IN GRAVELLY SAND

The bed of gravelly sand is prepared in four layers in the testing chamber. Before installation of model pile, the first layer (thickness 190 mm) of soil is placed and fully compacted. Then the model pile is installed at the centre of the testing chamber using templates. After that, the second, third and fourth layers (thickness of layers 270 mm) of soil are filled in the chamber and compacted to the required density. In all tests, the pile has embedment length of 810 mm. The unit weight of soil in model tests is maintained as 19.5 kN/m$^3$. Experimental setup is shown in Fig. 3.8. Erection of pile group is shown in Fig. 3.9.

![Fig. 3.8 Experimental set up](image)
Fig. 3.9 Erection of model pile group (2 × 2) and preparation of gravelly sand bed: (a) Compacted up to third layer and (b) compacted up to top
The pile groups are formed by screwing the piles to pile caps of suitable sizes using sockets. The head condition of single piles is free head condition same as that of the referred field test. The pile caps are of 20mm thick aluminium plate, 20mm steel plate and 20mm wooden plank. A flexible wire rope was connected to the pile cap and taken over a pulley attached to loading frame. The load is applied by a placing dead weights on the load hanger attached to the wire rope. The lateral load was applied at an eccentricity of height of 100mm above the surface of the soil bed. The lateral loads are applied in increments and are maintained for a period of 30 minutes to allow the deflection to stabilize. The load applied is measured accurately with the help of a load cell and deflection of the pile cap was measured using LVDT. The overall testing programme is presented in Table 3.4.

Table 3.4 Programme for tests on model piles embedded in gravelly sand

<table>
<thead>
<tr>
<th>Configuration of Model Pile</th>
<th>SINGLE PILE</th>
<th>2 x 2 PILE GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of materials used in model pile</td>
<td>Aluminum</td>
<td>Steel</td>
</tr>
<tr>
<td>Length to diameter(L/D) ratio</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Spacing to diameter (S/D) ratio</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Eccentricity(mm)</td>
<td>100, 150, 200</td>
<td>100, 150, 200</td>
</tr>
<tr>
<td>Slope (Degree)</td>
<td>0, 60, 45, 30</td>
<td>0, 60, 45, 30</td>
</tr>
<tr>
<td>Surcharge load (kN/m²)</td>
<td>3.2, 6.4, 9.6, 12.8, 16</td>
<td>3.2, 6.4, 9.6, 12.8, 16</td>
</tr>
<tr>
<td>Vertical load test</td>
<td>e =100mm</td>
<td>e =100mm</td>
</tr>
<tr>
<td>Lateral load = % of vertical load</td>
<td>0, 15, 30, 45, 60</td>
<td>0, 15, 30, 45, 60</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>Smooth and rough surface</td>
<td>Smooth and rough surface</td>
</tr>
</tbody>
</table>
3.5.3 LATERAL LOAD TESTS ON PILES EMBEDDED IN CLAY

The schematic sketch of the lateral load test setup on pile group embedded in clay is shown in Fig. 3.10.

Clay is mixed in separate chamber with required amount of water (water content $w = 43.5\%$) to get the required consistency ($I_c = w_{L_2} - w_{L_1}/I_P = 32\%$) of clay. The soil is allowed to saturate for two days. After placing the model pile in the center of the test chamber using template, uniformly mixed clay is placed and packed in the chamber in layers of 100 mm thickness and tamped with template in order to remove entrapped air to ensure homogeneous condition. Clay samples are taken at various depths. The water content, density, undrained shear (vane shear test) strength tests are conducted on the collected soil samples to confirm the homogeneity of the prepared clay bed.
Embedded length to diameter (L/D) ratio of the pile is varied from 15 to 40. Spacing in the direction of loading to diameter (S/D) ratio is varied from 3 to 7. Spacing in the direction perpendicular to loading is kept as 3D. All the tests are conducted at soft consistency of clay (Ic = 0.32). Based on the relative stiffness factor (Poulos and Davis 1980)

\[ K_{rc} = \frac{E_p I_p}{E_S L^4} \]  

(3.3)

Where \( E_p \) = modulus of elasticity of model pile materials (70 GPa), \( I_p \) = moment of inertia of pile section, \( E_S \) = secant modulus of soil (55 cu), undrained shear strength of clay \( c_u = 8 \) kPa and \( L = \) embedded length of pile. The pile is said to be rigid if \( K_{rc} \) is greater than \( 10^{-2} \) and flexible if \( K_{rc} \) is less than \( 10^{-5} \) (Poulos and Davis 1980). Piles having L/D ratio of 15 and 20 are rigid piles, L/D ratio of 30 are intermediate and L/D ratio of 40 are flexible piles.

Static lateral loads are applied on pile cap in increments (Fig. 3.10). Each increment of load is maintained for 30 minutes. A load cell attached between the pile cap and rope is used to measure the load carried by the pile group. Pile head and ground line deflections are measured using Linear Variable Displacement Transducers (LVDT). Bending Strain is measured along the embedded length of the pile from strain gauges pasted on the piles at various depths. The bending moment is calculated using the following expression

\[ M = \frac{E \epsilon r}{r} \]  

(3.4)

where \( E \) = Young’s modulus of the model pile material, \( I \) = Moment of inertia of the model pile, \( \epsilon \) = Measured bending strain and \( r \) = Horizontal distance between strain gauge position (outside side surface of the pile) and neutral axis.

A 24 channel data acquisition system is used to monitor and store the data. The data acquisition system consists of a digital carrier frequency amplifier system of HBM make MGC plus (Model: AB 22A) with 24 channels. It is used to amplify the signals received from transducers. This amplifier system is connected to personal computer using communication processor with USB interface. CATMAN Professional software is used to acquire and analyse the data received from various types of transducers through the amplifier system.
3.6 SUMMARY

This chapter outlined the properties of the soil used for the experimental work. The scaling law and scaling factors used to select the model pile, properties and dimensions of model piles are presented. The experimental setups and test procedure used for static lateral tests on single piles and pile groups are explained. The details of soil bed preparation, configuration of pile group and detailed scheme of the test programme are presented in the later part of the chapter. Results of the experiments are analyzed, interpreted and discussed in chapters 4, 5 and 6 for piles embedded in sand, gravelly sand and clay respectively.