EFFECT OF ORIENTATION OF SINGLE PILE AND PILES IN PILE GROUP UNDER LATERAL LOADING

A Dissertation submitted in partial fulfillment of the requirement for the

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IN

GEOTECNICAL ENGINEERING

BY

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(ROLL NO. 2K14/GTE/21)

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CANDIDATE'S DECLARATION

I do hereby certify that the work presented is the report titled "**Effect of orientation of single pile and piles in pile group under lateral loading**" in partial fulfillment of the requirements for the award of the degree of "**Master of Technology**" in geotechnical engineering submitted in the Department of Civil Engineering, **Delhi Technological University, Delhi**, is an authentic record of my own work carried out from December 2015 to June 2016 under the supervision of **Dr. Amit Kumar Shrivastava** (Assistant Professor), Department of Civil Engineering.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

Nakul Negi

Date: 30 June 2016 (2K14/GTE/21)

CERTIFICATE

This is to certify that above statement made by the candidate is correct to best of my knowledge.

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ABSTRACT

Pile is a type of deep foundation and is generally used when the top ground surface has low bearing capacity. It is used to transfer heavy axial and lateral load to the deeper soil having high bearing capacity. In present investigation experiments has been carried out to find the effect of orientation of pile on lateral load deflection resistance of piles. Experiments were carried out on the physical model to investigate the behaviour of single pile and pile group under lateral load. The orientation of the pile is changed from vertical to inclined both positive and negative to the loading direction to study the effect of inclination on the lateral load deflection resistance of the pile and piles in pile group. The model pile is made up of steel and has outer diameter and inner diameter of 20mm and 19mm, respectively. The batter angle of inclined pile was kept 15^0 initially. The testing tank dimensions are chosen such that boundary effects are eliminated. The size of tank is 750 x 600 x 400 mm. Experiments were conducted on single pile and pile groups embedded in sandy soil under lateral loading. Load versus deflection curves results indicate lateral load deflection resistance of pile groups containing batter pile mainly depends upon the direction of inclined pile with respect to lateral loading application direction. The experimental investigation shows that the pile inclined in the direction of lateral load application i.e., negative battered pile offers greater lateral load deflection resistance followed by vertical pile and positive battered pile. Positive battered pile are those piles which have inclination in opposite direction of lateral load application. After finding out the effect of inclination direction of pile on lateral load deflection resistance, the effect of increasing batter angle on lateral load deflection resistance of the pile is studied. In the current investigation batter angle of $+20^o$, $+15^o$, $+10^o$, 0^o,-10^o,-15^o& -20^o is taken into consideration. Lateral load does not act continuously on structures therefore effect of reloading is also considered and investigated on single pile to find which orientation is best suitable for countering reloading effect caused by wind, sea waves, etc.

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CHAPTER 1

INTRODUCTION

1.1 Preamble

Pile foundation is often used in bridges and other structures to support the applied axial and lateral loads. Pile can be classified into different types depending on their alignment like material of construction, mechanism of load transfer, method of installation etc. Piles can be classified into vertical and batter pile based on the alignment of pile. Battered piles can be further sub categorised into positive and negative batter pile depending on inclination of pile with respect to the loading direction. In offshore structure's foundations and bridges battered piles are usually used to resist the lateral impact caused by wind and sea waves. The piles in a group behave differently than a single pile due to group interaction effect, which depends on centre-to-centre spacing between piles and pile type.

Axial load carrying capacity of piles have been studied by many researchers like Randolph, et al.,(1994), Olson (2002),Douglas (2002) and Anamali (2014) but a very few studies have been done on lateral loading of piles. For analysing the behaviour of laterally loaded pile groups the concept of subgrade modulus or considering the soil as an elastic continuum is used. Broms (1964) gave ultimate load analysis to predict ultimate lateral soil resistance and lateral deflections of piles. Meyerhof et al. (1981) suggested that the ultimate resistance per unit width of laterally loaded pile is greater than that of wall in homogeneous sand. Behaviour of single free headed model flexible vertical and batter pile under central inclined loads in two layered soil was investigated by Meyerhof and Yalcin (1992).He found that the ultimate capacity of pile is found to depend on the soil layering, load inclination and inclination of pile. Prasad and Chari (1999) measured actual soil pressure distribution in rigid model pile, embedded in sand, along its length across the diameter. Load displacement response, ultimate resistance and group efficiency with spacing and number of piles in a group was investigated by Patra and Pise (2001). Zang(2005) developed a method for determination of ultimate soil resistance of piles including frontal side resistance and side shear resistance in cohesion less soil. The batter angle of inclined piles was kept 15 degree initially afterwards pile having batter angle 20 degree and 10 degree also used. A wedge is cut down from a wooden plank having angle with horizontal 75^{o} then the wedge is placed vertically over the pile cap and by sliding the drilling machine over hypotenuse of wedge hole is made on the pile cap and the desired batter angle of 15° is achieved similarly other angles also achieved which is explained in details under *Chapter 3*. The pile inclination influences the ultimate soil resistance transferring some lateral to axial load and consequently modifies the load-deflection curve of vertical pile. This report presents the result of experiments conducted on model piles and pile group embedded in sand subjected to lateral loading.

The lateral load induced on the pile foundation generates deflections, rotations, bending moments or translations whereas the lateral load on pile group causes lateral movements, vertical movement rotations of piles and also rotation of the pile cap as presented in the Figure 1.1 and 1.2. If the rotation of the pile cap is not significant, then the piles can be assumed to move only in the horizontal direction.

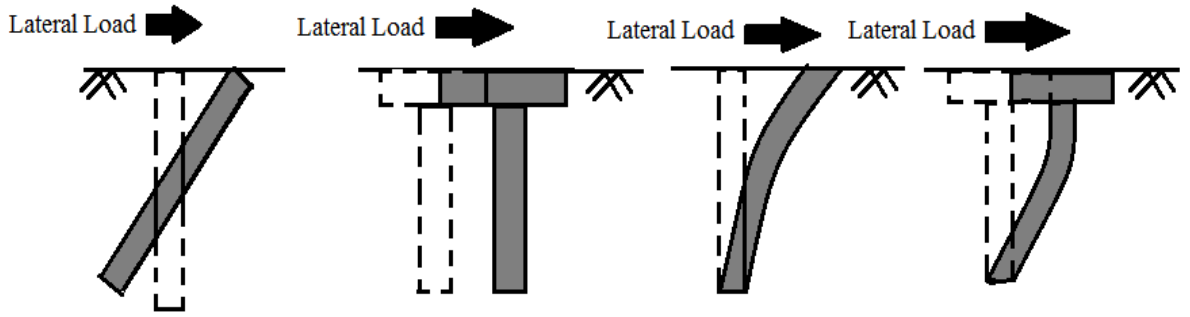

Fig. 1.1: Response of a single pile under lateral load

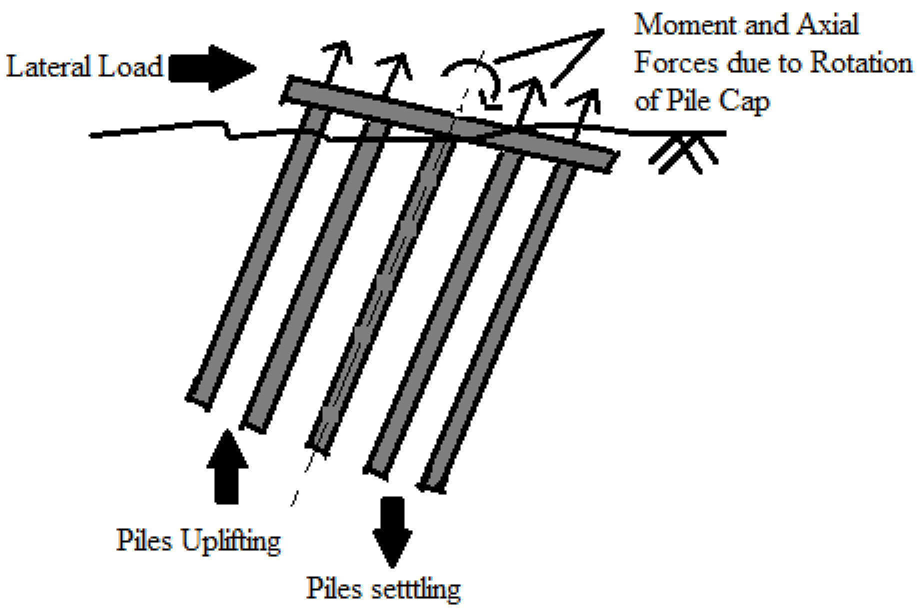

Fig. 1.2: Response of pile group under lateral load.

The displacement of the pile caused by the applied lateral load displaces the soil in front of the pile in the loading direction. This displacement generates compressive stresses, shear stresses and strains in the soil that resist the pile movement as shown in the Figure 3. This is known as lateral resistance of pile or soil reaction.

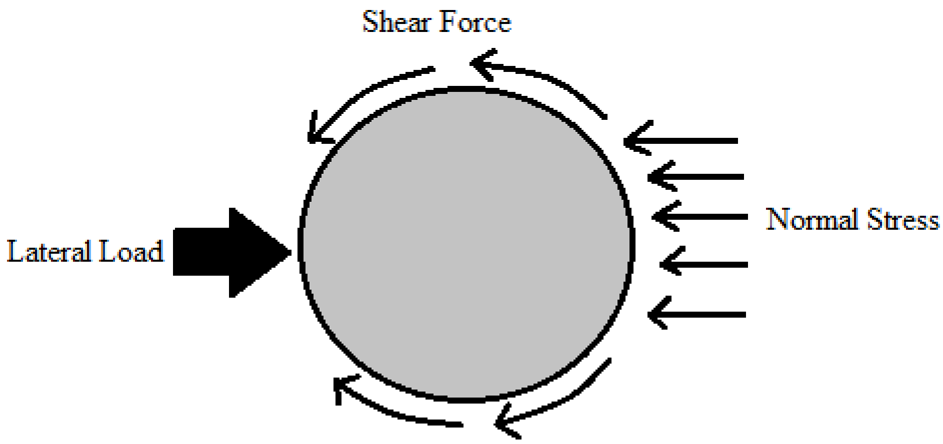

Fig. 1.3: Soil reaction over cross section of pile.

1.2 Objective of Dissertation

The objective of this study is to analyse the effect of orientation of pile on lateral load deflection resistance. Model tests were conducted in laboratory for ten cases of different arrangements of piles to find which can offer greater resistance towards deflection due to lateral loading. Experiments were conducted on piles embedded in locally available sand. Cases considered are listed below:

Case 1: Vertical Pile
Case 2: Negative Batter Pile
Case 3: Positive Batter Pile
Case 4: 1 Vertical and 1 Negative Batter Pile
Case 5: 1 Vertical and 1 Positive Batter Pile
Case 6: 2 Positive Batter Piles
Case 7: 2 Negative Batter Piles
Case 8: 4 Vertical Piles
Case 9: 2 Vertical and 2 Negative Batter Piles
Case 10: 2 Vertical and 2 Positive Batter Pile.

After knowing the effect of pile inclination on lateral load deflection resistance, following objectives are fulfilled by conducting experimental studies:

(i) Effect of increasing batter angle on lateral load deflection resistance (+20°, +15°, +10°,0°,-10°,-15°,-20°).

(ii) Effect of reloading on single pile because lateral load does not act continuously on the structures.

1.3 Scope of the Project

The project's topic is "*Study of the effect of orientation of single pile and piles in pile group under lateral loading*". Piles are very commonly used in civil engineering construction work where the soil present below the structure does not have sufficient bearing capacity to take load. Thus piles are used to transfer load to deeper depths where soil have good bearing capacity. Piles used to transfer axial and lateral loads by end bearing and skin friction mechanism.

Normally vertical piles are used in construction which carries high axial loads but very little lateral loads. There is greater chances pile foundation failure under high lateral loads. Present experimental studies will allow us to optimise performance of piles under lateral loads by conducting experiments on single pile and different pile groups. The load deflection curves obtained from experiments for different cases are analysed to get inclination of pile in the direction which with respect to lateral load application offers better deflection resistance. Experimental studies are further conducted on pile with different batter angle to get load deflection curves which are analysed to get better lateral load deflection resisting pile. Effect of reloading is also considered in the experimental studies because lateral load does not act continuously. The result of present study will be very helpful in increasing performance of pile under high lateral loads and will reduce chances of foundation failure.

1.4 Battered Piles

Vertical piles are used in foundations to take normally axial loads and small lateral loads. When the horizontal load exceeds the permissible bearing capacity of vertical piles in that situation batter piles are used in combination with vertical piles. Batter piles are also called inclined piles. The degree of batter that is angle made by pile with vertical may go up to 30 degree. A pile is said to have positive batter if its inclination with the vertical (i.e. batter angle) is in direction opposite to that of that of acting lateral loads.

A pile is said to have negative batter if it is loaded in the direction same as that of the batter angle.

The former is also termed "out batter pile" and later as "in batter pile". A vertical pile is a special case of batter pile in which batter angle is zero.

Batter piles are widely used in offshore structure due to their considerable resistance against lateral loading induced by wind, ship impact, water wave, etc.

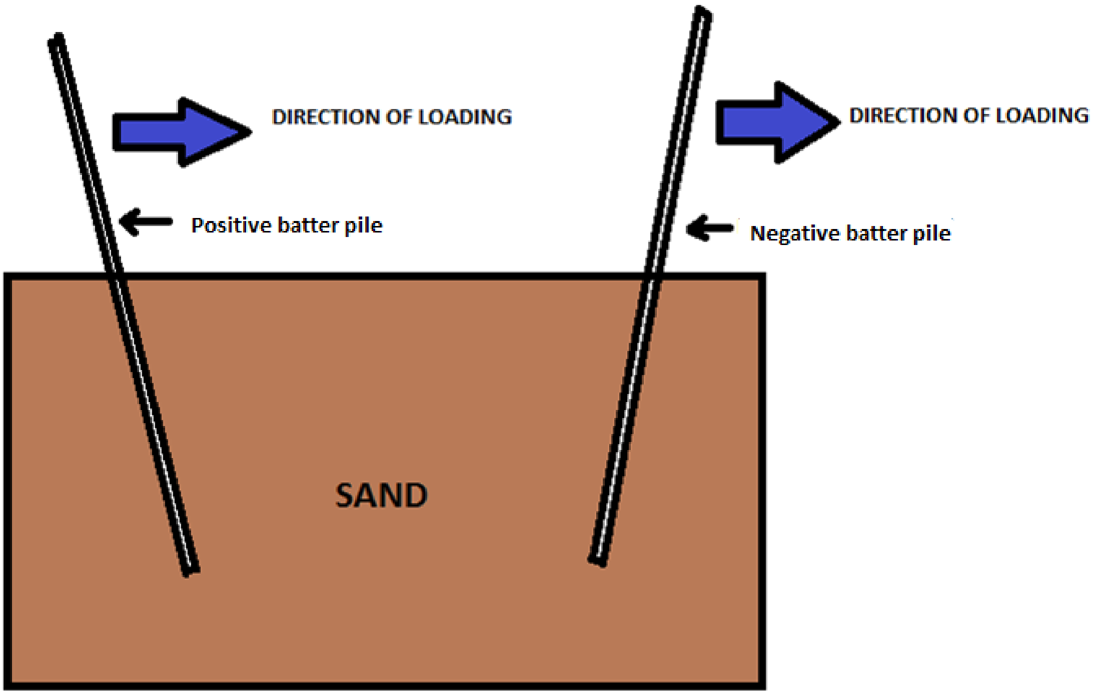

Fig 1.4: Sketch of positive and negative batter pile.

1.5 Organisation of Dissertation

The report is subdivided into 7 chapters. *Chapter 1* express the importance of the matter and objective of the study. *Chapter 2* presents the literature review available on this topic. *Chapter 3* and *Chapter 4* is for the methodology, characteristics of soil by laboratory work and theory involved in this dissertation work. *Chapter 5* includes the experimental program for this study. The results and the observations are included in *Chapter 6*. Finally in *Chapter 7* summary and conclusions of the dissertation work are discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

To understand the lateral load behaviour of pile/pile groups, experiments are conducted; where pile/pile groups are categorized into full-scale test, centrifuge and model tests. Because full scale tests have technical difficulties, high cost and uncertainties, they are not easy to perform. As the result there are only a few full-scale tests have been performed since early nineteenth century, comparison to centrifugal tests that can simulate the actual field condition have been conducted.

The existing analysis methods can be classified into six methods on the basis of assumptions applied for modelling the pile and soil behaviour:

1) An analytical model based on the lateral earth pressure theory was developed by Hansen (1961) and Broms (1964) which helped to analyse the lateral load behaviour on short pile foundation.

2) Winkler (1867) proposed the subgrade resistance with the linear characteristic of spring representing the soil resistance behaviour which was then related to the load-displacement behaviour of pile.

3) Poulos (1971) developed a model based on an elastic continuum approach which assumes both the soil and pile as elastic materials. This model was used to analyse lateral load behaviour using the finite difference technique.

4) To analysis lateral load tests, finite element method where the soil-pile interaction can be modelled easily is also used. Several computer programs were developed based on finite difference method and finite element technique.

5) The p-y curves is the most popular method which is used in researches. Here, Winkler's approach was modified by Matlock (1970) and Reese (1974) as they represented the soil as a non- linear characteristic material.

6) Strain wedge model, analyzed the behaviour of laterally loaded piles was developed by Norris (1986) and updated by Ashour et al. (1998), it considered the pile properties such as pile shape, bending stiffness, and head condition.

Hansen and Broms (1964) developed a model which was applicable to only short pile foundation, and that the finite element method and finite difference method require long process, so these models will not be covered in detail. The p-y curves method is found to be the most reliable method.

2.2 Overview of Research Papers

There is a very limited research that has been done in the field of lateral loading as compared to axial loading and some of these researches are given below in brief.

Reddy and Ayothiraman (2015) conducted experiments on model pile to find the effect of combined loading i.e., uplift and lateral loading on displacement of pile. Woods scaling law was used for scaling and experiments were carried out to get deflection under different loads. The experimental studies led to the conclusion that the ultimate lateral capacity increases with an increase in pile length which could be due to the increase of the passive resistance with the increase in pile length. However, for long flexible piles i.e., L/d> 23 it is found that ultimate lateral load remains practically the same. The ultimate lateral capacity and ultimate uplift capacity of the pile increases considerably under combined loading.

Kershaw and Luna (2014) conducted a full scale experiment which was performed to study the effect of combined loading i.e., axial and lateral loading. The testing program included two lateral load tests and four combined-load tests. The axial and lateral load capacity was initially determined. The axial load applied in combined load test was 50% of the ultimate axial load. The axial load is kept constant and lateral load was kept on increasing until the maximum lateral deflection of the equipment is achieved i.e., 63 mm. The combined load test result shows that maximum ratio of lateral load to axial load of about 0.6.However the experiments were conducted on stiff clay and it is seems that application of a static axial load has a minute effect on the lateral behaviour of micro piles installed in stiff clay.

Khari et al. (2013) conducted an experimental study on pile and pile group under lateral loading. Experiments were carried out on 12 model pile groups with embedded length to diameter ratio is equal to 32 into loose and dense sand, spacing from 3 to 6 times pile diameter in series and parallel arrangement. The experimental studies lead to the conclusion that the ultimate lateral load was increased to 53% if spacing and diameter of pile ratio increase from 3 to 6.

Hirani et al. (2013) conducted experimental study on pile group to see the effect of batter angle on pile vertical load carrying capacity. In the experimental studies test was performed on pile with different batter angles and load deflection behaviour of pile is compared with the vertical pile. Through experimental studies it is found that vertical load carrying capacity for batter angle 5^o is 40-50% more than vertical pile and 9-10% more when pile have 10^o batter angle. The experimental study and load deflection curve analysis shows that vertical load carrying capacity of batter pile firstly increases till 5^0 batter angle and after that at starts decreasing; 5^o is the optimum angle for vertical loading.

CHAPTER 3

LABORATORY TESTING

There are several laboratory tests which were performed on soil which is used for the experimental study. The procedure of testing was as per IS 2720 and observations of the testing is described under *section 3.1 to 3.4* and soil properties are tabulated in table 3.3.

3.1 Specific Gravity

The specific gravity of a soil sample is defined as the ratio of the weight of a given volume of soil solids to the weight of an equal volume of distilled water at 4^{o}C. Specific gravity is denoted by symbol 'G'. Experiment was conducted as per the IS 2720 (Part 3/ Section 2). Specific gravity can be determined by:

$$G = \frac{(W2 - W1)}{(W2 - W1) - (W3 - W4)}$$

where,

w_1 = Weight of Pycnometer

w_2 = Weight of Pycnometer + Soil

w_3 = Weight of Pycnometer + Soil + Water

w_4 = Weight of Pycnometer + Water

Table 3.1: Calculation of specific gravity of soil

	Sample 1	**Sample 2**	**Sample 3**
w_1 (g)	694.32	696.20	697.90
w_2 (g)	896.30	895.32	898.12
w_3 (g)	1690.00	1689.15	1689.52
w_4 (g)	1564.11	1563.90	1565.93
G	2.65	2.69	2.61

The average of the above three values was taken as the value of specific gravity of the soil sample i.e. **G =** [(2.65+2.69+2.61)/3]=**2.65**

3.2 Particle Size Distribution

The dry sieve analysis of the soil was conducted. Experiment was conducted as per the IS 2720 (Part 4). The sieves were arranged in a decreasing order from top to bottom. The mass of soil retained on each sieve was noted down and percentage finer was calculated and it was plotted against sieve size on a semi log graph paper sheet.

Table 3.2: Result data for sieve analysis of the soil

Sieve size (mm)	Mass retained (g)	Percent mass retained	Cumulative percent retained	Percent finer
4.75	16.56	1.66	1.66	98.34
2.36	33.7	3.37	5.03	94.97
1.18	57.52	5.75	10.78	89.22
0.6	2.48	2.48	13.26	86.74
0.3	661.16	66.12	79.38	20.62
0.15	181.8	18.18	97.56	2.44
0.075	4.97	0.5	98.06	1.94
Pan	19.44	1.94	100	

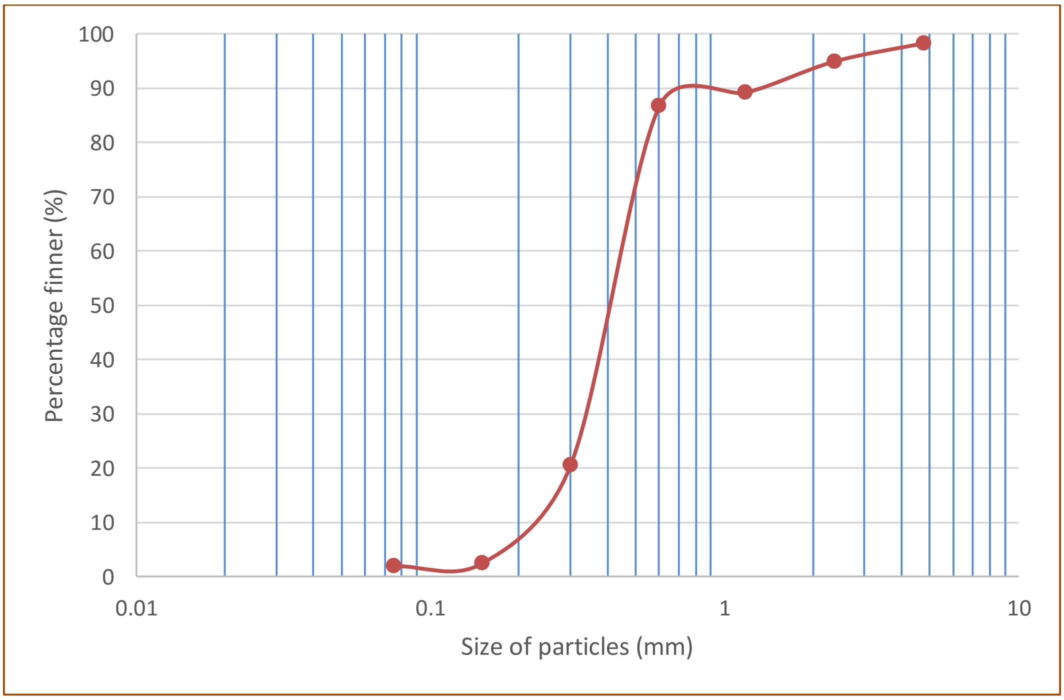

Fig. 3.1: Grain size distribution curve

From the grain size distribution curve the value of D_{10}= 0.22, D_{30}=0.33 and D_{60}=0.45

where, D_{10}=particle size such that 10 percent of sample is finer than this size.

D_{30}=particle size such that 30 percent of sample is finer than this size.

D_{60}=particle size such that 60 percent of sample is finer than this size.

The coefficient of uniformity, $C_u = D_{60}/D_{10} = 0.45/0.22 =$ **2.04 mm**

The coefficient of curvature, $C_c = (D_{30})^2/(D_{10}*D_{60}) = 0.33^2/(0.22*0.45)=$**1.10mm**

For sand to be well graded $C_u \geq 6$ and $1<C_c<3$ but the conditions are not satisfied, therefore on the basis of C_u and C_c the soil is classified as **poorly graded sand (SP)**.

3.3 Direct Shear Test

The direct shear test was carried on the sand sample to determine the cohesion (c) and angle of internal friction (Φ) of the soil. Experiment was conducted as per the IS 2720 (Part 13). The soil specimen was subjected to three different types of loading i.e. 0.5 kg/cm^2, 1 kg/cm^2 and 1.5 kg/cm^2. The maximum shear force corresponding to the normal stress applied is plotted and the equation of the trendline is obtained to get the desired parameter i.e. cohesion and angle of internal friction of the sand.

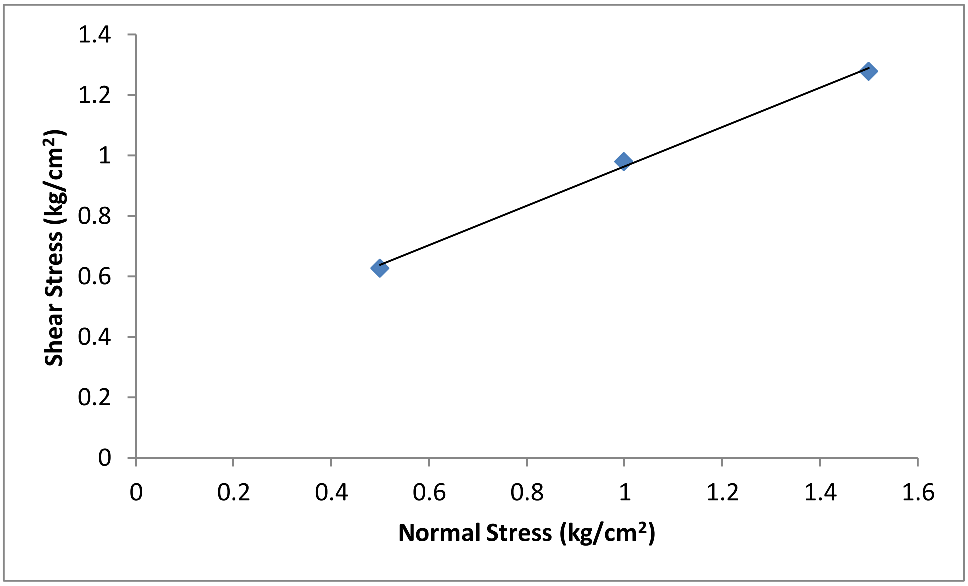

Fig. 3.2: Direct shear test graph

The cohesion of the sand is found out by x intercept of the graph which is negligible as expected for the case of sand, so it is taken as zero for the calculations. The equation of line is $y = 0.65x + 0.313$.

The angle of internal friction is the $\tan^{-1}$ of the slope of trend line which is obtained as 33^0.

3.4 MODIFIED PROCTOR COMPACTION TEST

This method is used to determine the maximum dry density of a soil sample. The soil is kept in a mould in five layers and 25 blows of hammer are applied to each layer. The test is iterated many times at different water content to obtain varying densities. A graph is plotted between water content and density of the soil at the corresponding water content. The peak of the graph enables us to compute the maximum dry density of the soil sample and water content in agreement with the above density is the optimum moisture content of the soil sample.

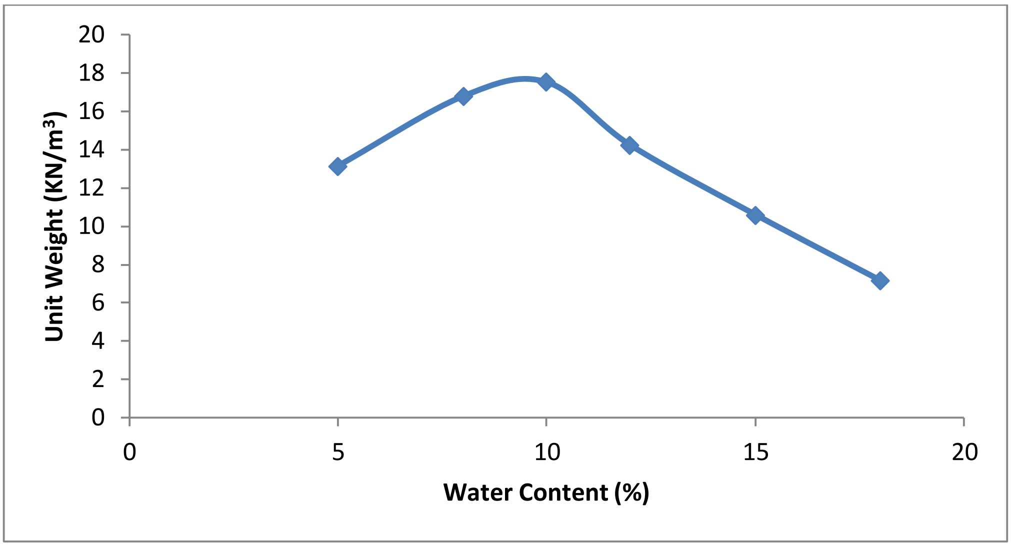

Fig. 3.3: Graph of compaction curve

Table 3.3: Summary of Soil properties

Description	Value
Natural water content, w	3.77%
D_{10}(mm)	0.22
D_{30}(mm)	0.33
D_{60} (mm)	0.45
Coefficient of Uniformity, C_u	2.04
Coefficient of Curvature, C_c	1.10
Specific gravity, G	2.67
Maximum dry density(kg/m^3)	1795
Minimum dry density(kg/m^3)	1285
Angle of internal friction(degree), Φ	33

CHAPTER 4

METHODOLOGY

To understand the effect of orientation of pile on the lateral load deflection resistance experimental studies are carried out with the help of load deflection curve which are obtained by conducting experiments on different piles and pile groups and by comparing them. The aim of study is to provide information that will assist in development of pile foundation which can with stand high lateral loads to avoid foundation failure. The whole methodology used for present experimental study is explained in further sections i.e., *section 4.1* to *section 4.6*.

4.1 Preamble

Model tests were conducted in laboratory for ten cases of pile and pile groups to find which can offer greater resistance towards lateral loading deflection. Dimensions of pile were modelled using proper scaling laws and boundary effect was also taken into consideration while fabricating set up. Experiments were conducted on piles embedded in locally available sand and the result of each case is compared.

Cases considered are listed below:

Case 1: Vertical Pile

Case 2: Negative Batter Pile

Case 3: Positive Batter Pile

Case 4: 1 Vertical and 1 Negative Batter Pile

Case 5: 1 Vertical and 1 Positive Batter Pile

Case 6: 2 Positive Batter Piles

Case 7: 2 Negative Batter Piles

Case 8: 4 Vertical Piles

Case 9: 2 Vertical and 2 Negative Batter Piles

Case 10: 2 Vertical and 2 Positive Batter Pile.

Case 1 to 3 was analysed for observing the behaviour of single pile. Case 4 to 10 was analysed for observing behaviour of pile group under lateral loading out of which case 4 to 7 is for pile group having two piles and case 8 to 10 is for pile group having 4 piles.

After finding out the effect of inclination direction of pile on lateral load deflection resistance, the effect of batter angle on lateral load deflection resistance is studied. Batter angle of +20^o, +15^0, +10^o, 0^o,-10^o,-15^o& -20^o is taken into consideration. Effect of reloading is also considered in present investigation for the single pile.

4.2Justification of Model Studies

Although, Full scale field test are the absolute solution to all engineering problems, it has a few setbacks also, like economic constraints, availability of time and other practical difficulties which are experienced during a field testing program. To avoid such hindrance, quantitative results are obtained from model tests. It is possible to probe the effect of some of the important variables by testing under proper control conditions that control the behaviour by keeping other minor factors constant. Experiments are conducted to investigate that in which direction pile should be inclined with respect to lateral loading application direction for better resistance towards lateral load displacement. Effect of increase of batter angle as well as effect of reloading on the pile is also studied with the help of experiments. Model pile experiments conducted in laboratory and conclusions are deducted which may be verified by full scale test. These results are useful for getting a fair idea regarding the effect of lateral deflection resistance of pile due to the orientation pile.

4.3Experimental Setup

The proposed experimental set up used for the experimental study of the effect of orientation of pile on the lateral load deflection resistance is show in figure 4.1. The experimental set up requires one dial gauge with 0.01 mm least count for measuring lateral deflection caused due to application of lateral loading and the deflection for each load increments is noted down which will leads to load-deflection curve. The modelling of piles and selection of all the experiment accessories are described in details under *section 4.4.* The actual experimental set up which is used for the study is shown in figure 4.2 and the whole procedure of experimental study is described in detail under *section 4.6.*

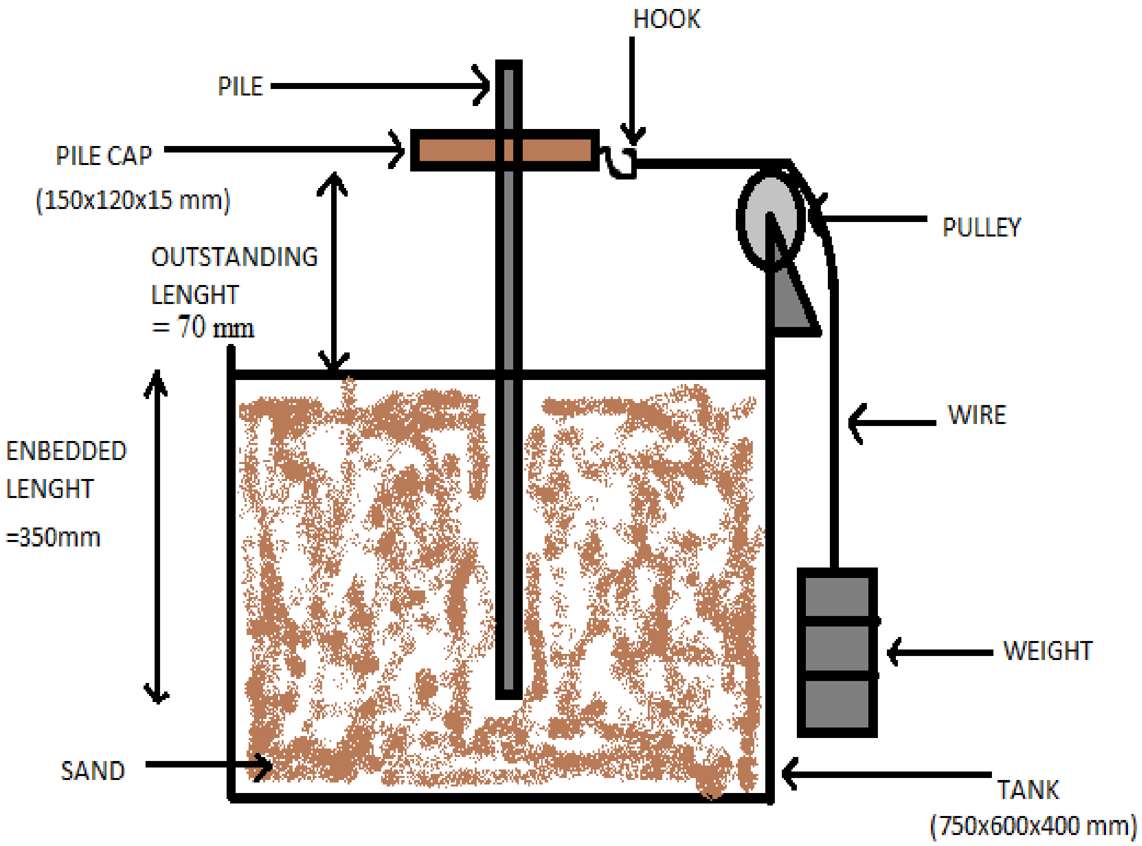

Fig 4.1: Schematic diagram of experimental setup.

Fig 4.2: Experimental Setup

4.4Materials used

4.4.1 Model piles

Steel pile having outer diameter 20 mm and internal diameter 19 mm is used as model pile. David Muir Wood's (2004) formula is used for scaling.

$EI_p / EI_m = n^{4.5}$

Where, EI_p is flexural rigidity of prototype pile,

EI_m is flexural rigidity of model pile

n is scaling factor.

For an assumed M25 grade reinforced concrete pile of diameter 600 mm, the scaling factor are estimated as 18.83 .The L/d ratio of 17.5 is used in the present investigation. The prototype length is 10.5 meter and the dimensions of the model pile used are given below:

Pile length= 800 mm

Pile outer diameter= 20 mm

Pile inner diameter= 19 mm

The outstanding length is kept 70 mm which is greater than 50 mm, thus no resistance is caused due to pile cap and soil interaction which will ensure that pile is not getting any resistant because of pile and pile cap contact.

4.4.2 Pile caps

The pile caps were necessary for keeping the piles in groups with the different arrangements. The pile caps are also necessary to hold all the piles in group together so that when lateral load is applied, it distributes the load among all the piles simultaneously and uniformly. Pile cap made up of timber is used since the only soul purpose of pile cap is to distribute the load uniformly. The dimensions of pile cap are given below:

Pile cap length= 150 mm

Pile cap breadth= 120 mm

Pile cap thickness= 15 mm

According to IS 2911 (Part 1), if the load carrying capacity of pile is mainly due to the friction then minimum centre to centre spacing of model pile should be greater than or equal to 3 times the diameter of model pile. Therefore centre to centre spacing of model pile should be greater than or equal to 3*20 i.e., 60 mm, thus centre to centre spacing is kept 100 mm which is greater than minimum centre to centre spacing of model piles.

4.4.3 Wire

Wire is used for transferring the load to pile cap. Wire should be strong enough to withstand the load which is passed over the pulley and attached to the hook embedded in the pile cap.

4.4.4 Pulley

The pulley arrangement is used for smooth movement of wire to avoid any friction between wire and test tank boundary so that tank boundary do not contribute to lateral load resistance of model pile, here pulley having 7 cm diameter is used for this purpose.

4.4.5 Testing Tank

The dimension of testing tank is decided on the basis of the effective stressed zone of soil mass from the edge of the foundation. For the laterally loaded pile boundary effect is more predominant within the area 10 times the diameter of model pile (Matlock 1970 and Rao et al. 1996, 1998). Therefore to eliminate boundary effect due to lateral loading dimension of tank fixed greater than 10 times the diameter of model pile i.e. 10*20= 200 mm. The dimensions of testing tank are decided by keeping in mind the elimination of boundary effect. The dimension of testing tank used is given below:

Tank length= 750 mm

Tank Breadth= 600 mm

Tank Height= 400 mm

4.4.6 Dial gauge (0.01 mm least count)

Dial gauge is placed on pile cap for noting down deflection readings for each load increment which enabled us to get load deflection curve for studying the effect of orientation of pile on the lateral load resistance capacity of model piles and pile groups.

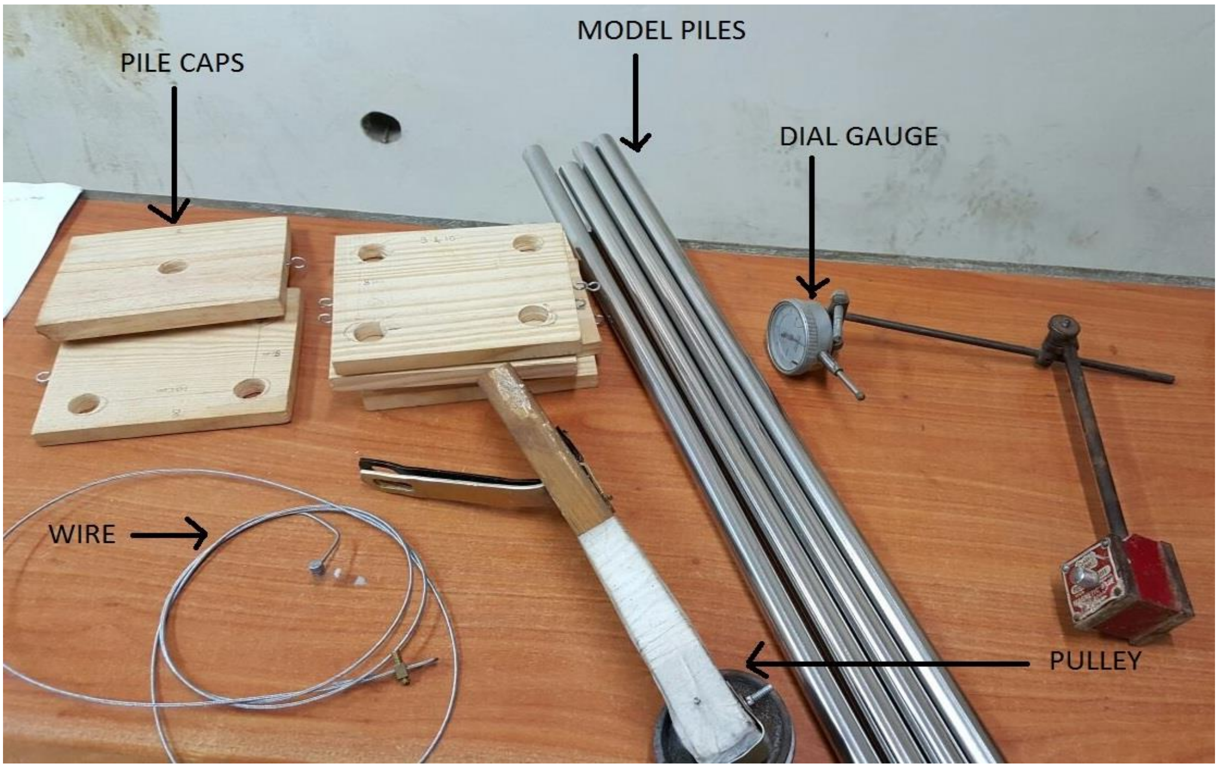

Fig 4.3: Model piles, pile caps and accessories.

4.5Batter angle achievement

For carrying out present experimental investigation pile having batter angle +20°,+15°,+10°,-10°,-15° and -20° is required.

For achieving these batter angles it is required to drill an inclined hole in the pile cap.

Following steps are followed for achieving the desired batter angles:

(i) Take 3 wooden planks and with the help of protector, scale and pencil, a line is made on the planks with an angle 80°, 75° and 70°. [refer fig. 4.4 (i)]

(ii) Saw is used to cut down the marked part from the wooden plank. [refer fig. 4.4 (ii)]

(iii) The wedge having angle 80° is placed vertically over pile cap on the position where hole is to be made.

(iv) By sliding drilling machine on the inclined slide of the wooden wedge desired batter angle is achieved i.e. $90-\Theta = 90-80=10^{o}$. [refer fig. 4.4 (iii)]

(v) Similarly, steps 3 and 4 are repeated for angle 75° and 70° for batter angle 15° and 20°.

Fig4.4: Steps followed for achieving desired batter angle.

4.6 Testing Procedure

The static lateral load tests are conducted on piles as per the procedure recommended by IS: 2911 (Part 4) and Ayothiraman & Boominathan. The initial reading in the dial gauges is noted down before the application the load. The static lateral load is applied in increments by adding dead weights through the loading arrangement as shown in fig. 4.1 and 4.2. For each load increment, the horizontal deflection of the pile head is measured and noted down.

The steps for conducting the experiment are as follows:

4.6.1 Filling of tank

The tank will be filled up by sand up to height of 380 mm. The summary of properties of sand used is mentioned in table 3.3. During the filling up of tank sand is divided into four layers and each layer is compacted with the help of hammer. The density and relative density of sand is 1679 kg/m^3 and 82% respectively. A pulley arrangement is then attached to the tank for application of lateral load.

4.6.2 Driving of piles

The pile cap was placed exactly at the centre of the testing tank in such a way that the wire passing over pulley passed through the particular hook which was attached to the pile cap. Then the pile cap is placed over the sand to take impression of holes on the sand surface. Then one model pile was kept above the impression of the hole on the sand surface. The pile was held vertically or inclined as required for various holes and hammered gently to required embedment depth. Similarly the other piles were driven into the sand to required embedment depths.

4.5.3 Application of lateral load

After driving the required number of piles at the required spacing and inclination, the top of the pile was connected by the pile cap. A dial gauge was attached to the pile cap to note down the horizontal deflection of the pile group. Then the free end of the wire is connected to the hook of the pile cap. The other end of the wire is attached to hanger and the wire was passed over the pulley. The load was increased on the hanger from 0.75 kg to 7.5 kg i.e. 7.36 N to 73.57 N. After each increment of 0.75kg (7.35 N) the dial gauge reading is noted from which load deflection curve for all the ten different cases is obtained.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Effect of pile inclination direction

Model tests were conducted in laboratory for ten cases of pile and pile groups to find which can offer greater resistance towards lateral loading deflection. The results obtained by conducting experimental studies on ten different cases are discussed under *section 5.1.1 to 5.1.10*.

5.1.1 Case 1: Vertical pile

In case 1 which is the case of single vertical pile two L/d ratios are considered i.e., 17.5 and 15 to see the effect of varying L/d ratio on the lateral displacement resistance. In all the other cases L/d ratio is kept constant i.e., 17.5 because our aim of observing effect of varying L/d ratio on lateral load deflection resistance is fulfilled in this case only. Reddy and Ayothiraman (2015) also investigated effect of lateral load deflection resistance due to L/d ratio by keeping L/d ratio equal to 18, 28 and 38.

Table 5.1: Load –Displacement readings of single vertical pile for L/d ratio 17.5 and 15

S.No.	Lateral Load (N)	Deflection (mm)	
		L/d=350/20=17.5	L/d=300/20=15
1	7.36	0.71	1.05
2	14.71	1.47	1.80
3	22.07	2.10	2.74
4	29.43	3.28	3.64
5	36.79	3.54	4.18
6	44.14	4.00	4.42
7	51.50	4.52	5.00
8	58.86	9.16	10.36
9	66.22	10.28	13.52
10	73.57	12.10	15.20

Ultimate lateral load resistance of pile having L/d ratio 17.5 is when the pile displaces 12mm i.e., 73.17 N whereas pile having L/d ratio 15 is 63.73 N.

According to IS 2911 (1985) Part 4, Safe lateral load is minimum of (50% of load at which displacement is 12 mm and load at which displacement is 5 mm).

Therefore, Safe lateral load for L/d =17.5 is 36.58 N.

Safe lateral load for L/d =15 is 31.86 N

For comparing experimental result with the analytical method Brom's solution for lateral loading is used. He stated that the ultimate lateral resistance of a short piles embedded in cohesion less soil can be estimated making use of figure 9. In Fig. 9 the dimensionless quantity $Q_u/\Upsilon d^3 K_p$ is plotted against the D/b ratio for short piles where Q_u is the ultimate lateral load capacity of pile.

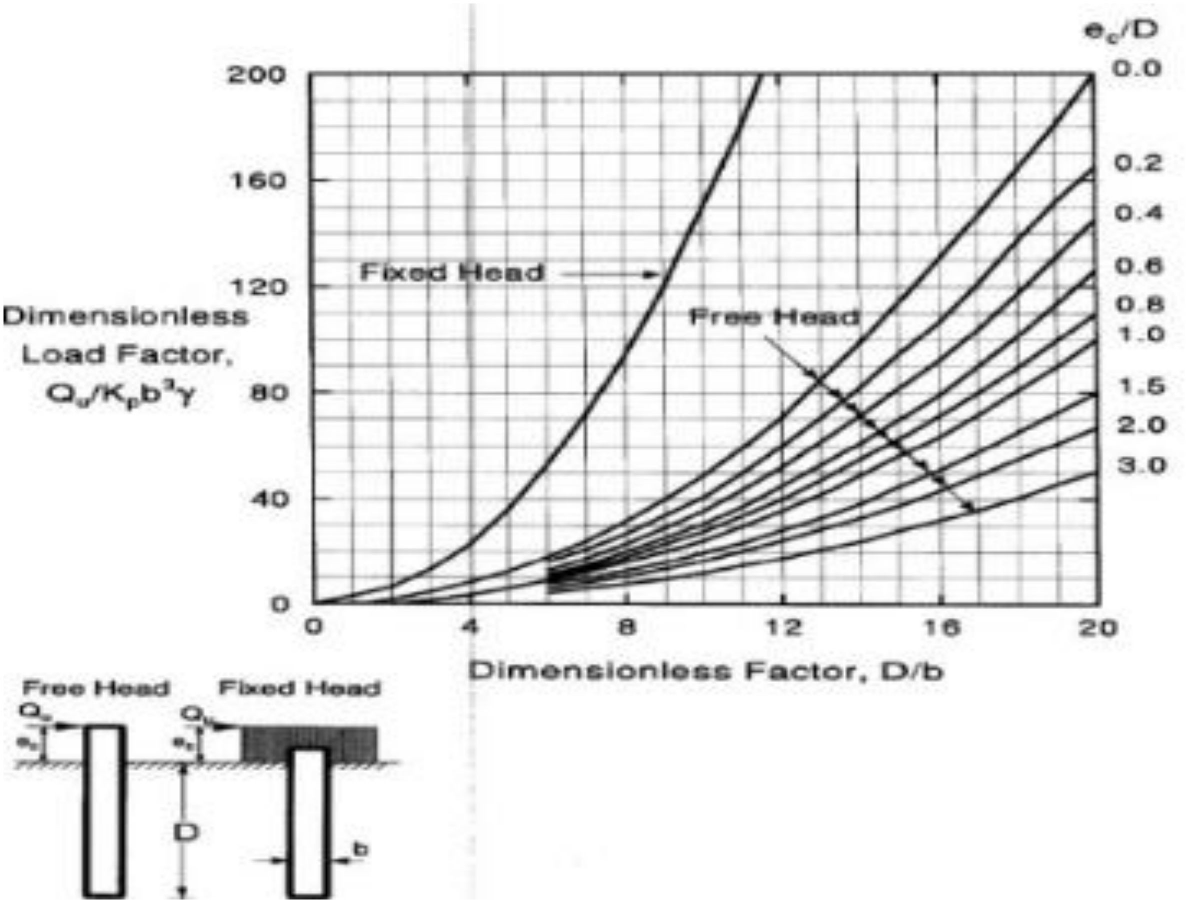

Fig 5.1: Ultimate lateral resistance of a short pile in cohesionless soil related to embedded length.

Ref: Jahan & Abedin (2012)

Coefficient of passive earth pressure, $Kp=\tan^2(45+\phi/2)=3.39$

Pile diameter, b=2 cm=0.02 m=d

Unit weight of soil, $\Upsilon=1679\ kg/m^3$

Depth of embedment= D=0.35 m,0.30 m=L

Eccentricity, e = 0.07 m

In cohesionless soil and short pile from figure 5.1 for D/b= 17.5 and e/D= 0.2, $Q_u/K_pd^3\Upsilon=120$ and for D/b=15, $Q_u/K_pd^3\Upsilon=95$

Therefore, ultimate lateral load capacity of pile comes out to be 53.60 N and 42.43 N for L/d ratio 17.5 and 15 respectively. The ultimate lateral load capacity of pile experimentally is found out to be 73.17 N and 63.73 N which is less than analytical value. Thus, method of analysis is conservative. Since is no well-established analytical theory to find lateral load resistance for battered pile calculations for comparison for only vertical pile with analytical method is carried out.

The load deflection curve for the single vertical pile having L/d ratio 17.5 and 15 is shown in fig. 5.2. From the graph it is clear that pile with higher L/d ratio gives higher resistance i.e., pile with L/d ratio of 17.5 displace less as compared to pile with L/d ratio 15 under same lateral loading since curve for L/d ratio 17.5 is above the curve for L/d ratio 15. For lateral load application of 73.57 N, the pile with L/d ratio 17.5 displacement recorded by dial gauge is 12.10 mm where pile having L/d ratio 15 shows displacement of 15.20 mm which is 25.62 % more than pile having L/d ratio 17.5.

Now the result of single vertical pile will be compared with the pile with inclination i.e, for positive and negative batter pile and comparison will be carried out to find out pile with which orientation is better for lateral load resistance. This purpose will be completed by the case 1 to 3 for single pile and case 4 to 10 for pile group.

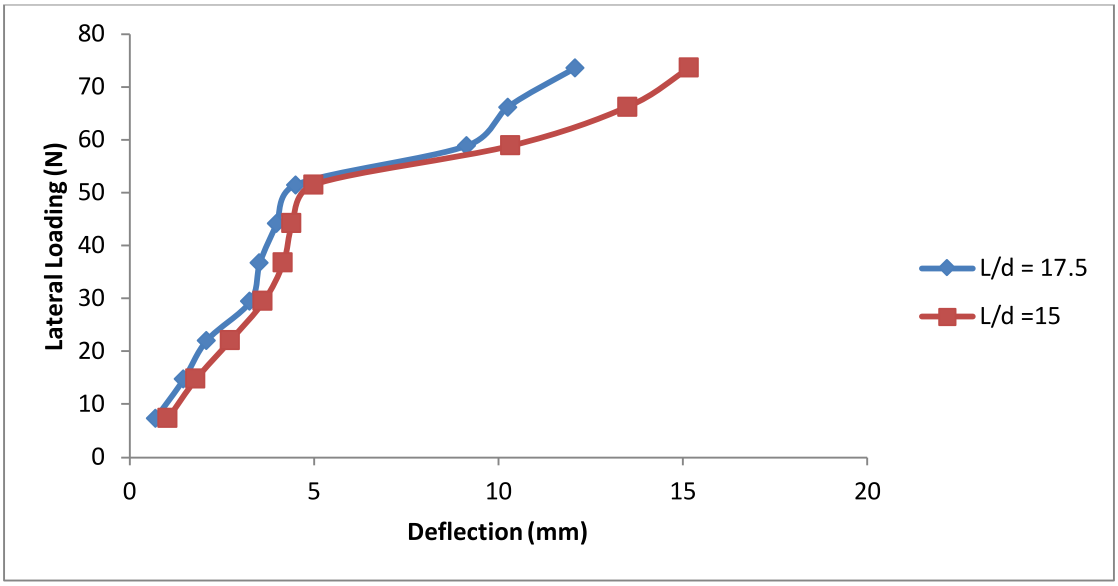

Fig 5.2: Load versus deflection curve for single vertical pile with L/d ratio 17.5 and 15.

5.1.2 Case 2: Negative Batter Pile

After analysing behaviour of single vertical pile when subjected to lateral loading now the pile is replaced by pile having inclination towards the loading direction .In this case single negative batter pile is considered and for each load increment pile cap its displacement is recorded by the dial gauge and recorded in table 5.2. For comparing negative batter pile case with the case of vertical pile refer figure 5.3 in which it can be clearly seen that negative batter pile curve lying above the vertical pile curve which implies that for same lateral load negative batter pile offers greater resistance to lateral load displacement as compared to vertical pile. For an instance at load of 73.57 N vertical pile displaces 12.10 mm whereas negative batter pile for same loading and same L/d ratio displaces only 4.11 mm. Thus by replacing vertical pile with negative batter pile reduces lateral load deflection by 66.03%. Therefore it can be concluded that negative batter pile is better choice for resisting lateral load as compared to vertical pile. Now the last case of single pile will be considered i.e., positive batter pile and it will be compared with case 1 and 2 to find out which type of pile offers better lateral load resistance.

5.1.3 Case 3: Positive Pile

This is the last case of single pile. In this case pile having inclination opposite to the direction of lateral loading is used. Positive batter pile deflection is compared to vertical and negative batter pile deflection for same lateral load. The deflection is recorded by dial gauge is 13.85 mm at 73.57 N lateral loading whereas the displacement was lesser in both of the above cases. Thus for 73.57 N lateral loading positive batter pile gives 14.46 % more deflection as compared to vertical pile. For better understanding refer figure 8 from which it is clearly seen that positive pile curve is lying below both the other curves which implies the lateral load deflection resistance of positive batter pile is least among the all and lateral load deflection resistance in case of negative batter pile is most.

Table 5.2: Load –Displacement readings of Case 1, 2 and 3.

S.No.	Lateral Load (N)	Deflection (mm)		
		Case1	Case 2	Case 3
1	7.36	0.71	-	0.80
2	14.71	1.47	0.01	1.56
3	22.07	2.10	1.00	2.65
4	29.43	3.28	1.36	3.74
5	36.79	3.54	1.48	4.16
6	44.14	4.00	1.66	4.45
7	51.50	4.52	2.37	5.12
8	58.86	9.16	2.90	10.00
9	66.22	10.28	3.56	12.17
10	73.57	12.10	4.11	13.85

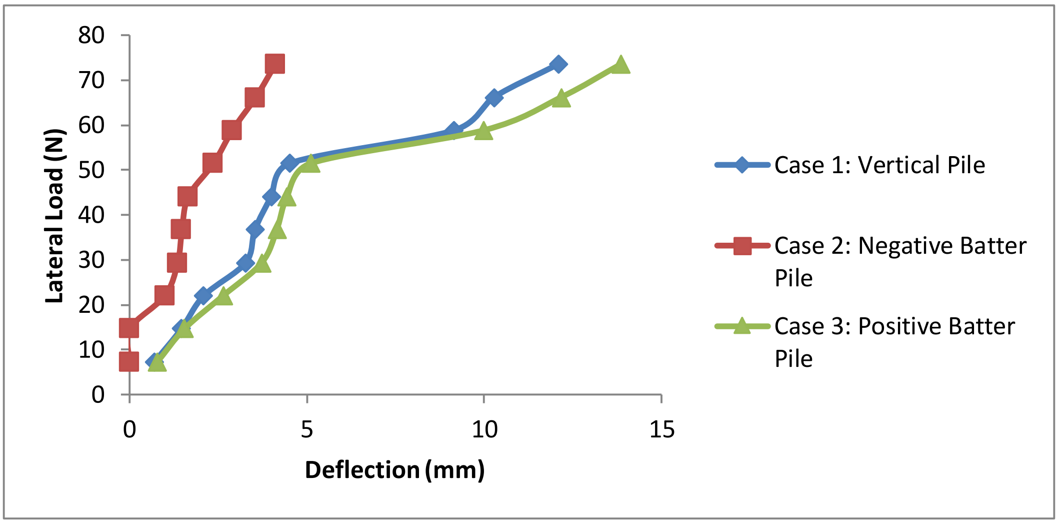

Fig 5.3: Load versus deflection curve for single vertical, negative and positive batter pile

5.1.4 Case 4: 1 Vertical and 1 Negative Batter Pile

After analysing effect of orientation of pile on lateral load displacement resistance in case of single pile the effect of pile group consist of two piles will be analysed and this objective will be achieved from case 4 to 7 in which different combination of vertical, negative and positive batter pile is chosen in a group of two piles. In this case pile group of one vertical and one negative batter pile is considered and displacement of pile group is recorded using dial gauge for each load increment which is tabulated in table 5.3 and load displacement curve for the same is shown in fig 5.4.

In comparison to case 1 in case 4 by introducing one additional negative batter pile lateral load deflection resistance increase significantly i.e., originally in case 1 on application of lateral load of 73.57 N deflection is noted was 12.10 mm whereas by addition of one negative batter pile deflection reduced to 1.88 mm which means deflection is reduced by 84.46%.

5.1.5 Case 5: 1 Vertical and 1 Positive Batter Pile

In this case negative batter pile is replaced by positive batter pile and displacement of pile is recorded by the help of dial gauge for each load increment. The data is tabulated in table 5.3 and curve is shown in fig 5.4.If we compare the case 5 and6 it is clear from the figure 5.4 that the curve for case 5 is lying below the curve for case 4 which means lateral load deflection resistance of pile group having positive batter pile is less than pile group having negative batter pile for the same lateral load application. At lateral loading of 73.57 N pile group consist of one vertical and one negative batter pile showing displacement of 1.88 mm whereas pile group consist of one vertical and one positive batter pile showing displacement of 2.45 mm.

On comparing case 5 with the case 1 i.e., the case of single vertical pile it is clear from the table 3 and 4 that the lateral load deflection resistance of pile increases on the addition of a single positive batter pile. On the application of lateral loading of 73.57 N deflection recorded in case one was 12.10 mm whereas in case 5 is 2.45 mm which means deflection is reduced by 79.75%.Thus introduction of negative batter pile reducing deflection by 23.26% than the case of introduction of positive batter pile.

5.1.6 Case 6: 2 Positive Batter Piles

In case 6 pile group of two positive batter pile is considered and displacement of pile group is recorded by using dial gauge for each load increment. Table 5.3 shows the displacement reading for each load increment, it can be seen that displacement in this pile group is largest as compared to pile group consist of one vertical and one negative batter pile or one positive batter pile. For lateral loading of 73.57 N displacement of 3.54 mm is recorded which is greater than case 4 and 5 which was 1.88 mm and 2.45 mm respectively. Thus it can be concluded that the positive batter pile gives better deflection resistance when grouped with vertical pile. For lateral load of 73.57 N deflection of pile group having only two positive batter pile is 44.48% greater than the pile group having one vertical and one positive batter pile and for the same lateral loading this pile group shows 88.29% more deflection as compared to pile group consist of one vertical and one negative batter pile. Thus using negative batter pile in combination with vertical pile proves to be batter choice rather than positive batter pile.

5.1.7 Case 7: 2 Negative Batter Piles

This is the last case to be considered for conclude the effect of orientation of pile on its lateral load deflection resistance in case of pile group consisting of two piles. In this case pile group of two negative batter piles is considered and pile group deflection is recorded for each load increment. After tabulating readings and plotting graph between load and deflection in fig 5.4 comparisons are done between case 4, 5, 6 and 7.

In case of two negative pile the displacement of pile group is minimum as compared to case 4, 5 and 6 as the curve for case 7 is above curve for case 4, 5 and 6 and the curve for case 6 is lying below all the cases of pile group consisting of two piles. For load of 73.57 N displacement is 1.48 mm in the present case whereas for the same loading case 4, 5 and 6 shows displacement of 1.88 mm, 2.45 mm and 3.54 mm respectively. Thus conclusion can be made that with the increase in number of negative pile in pile group lateral load displacement resistance of pile group increases. In case 4 vertical pile is replaced by negative batter pile to form case 7 to see the effect of increased number of negative batter pile over the lateral load deflection resistance of pile group, at loading of 73.57 N pile group having two negative batter pile gives 21.28% less deflection than pile group consisting of one vertical and one negative batter pile.

Table 5.3: Load –Displacement readings of pile group consisting of two piles

S.No.	LateralLoad (N)	Deflection (mm)			
		Case 4	Case 5	Case 6	Case 7
1	7.36	-	-	-	-
2	14.71	0.06	0.18	0.24	0.04
3	22.07	0.18	0.32	0.62	0.16
4	29.43	0.30	0.60	0.88	0.28
5	36.79	0.58	0.84	1.42	0.52
6	44.14	0.85	1.20	1.57	0.79
7	51.50	1.01	1.36	2.05	0.92
8	58.86	1.07	1.64	2.65	1.00
9	66.22	1.38	2.17	2.97	1.31
10	73.57	1.88	2.45	3.54	1.48

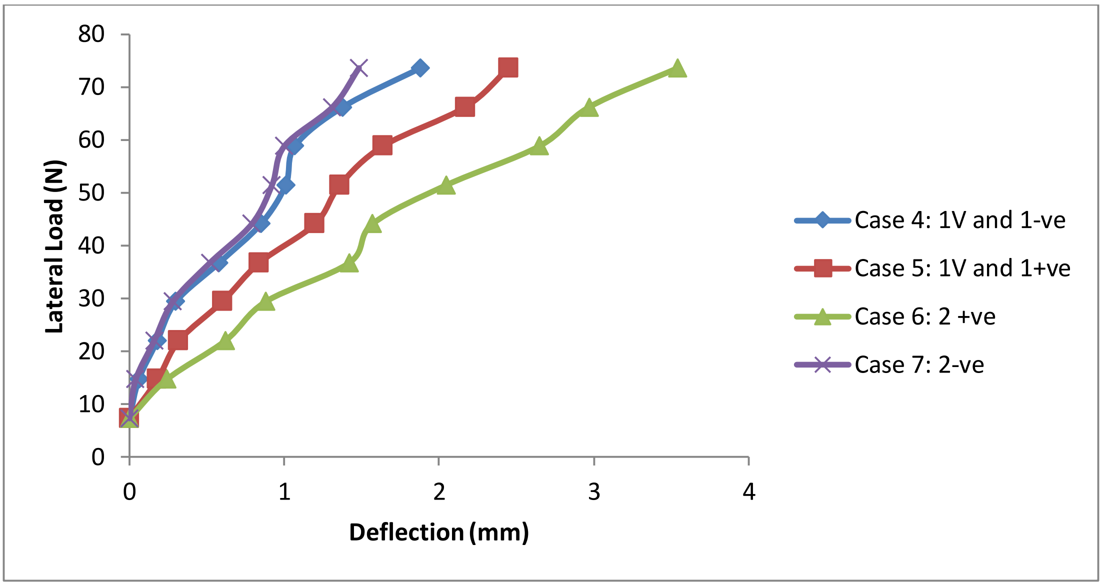

Fig 5.4: Load-Deflection curve comparison for case 4 to 7.

5.1.8 Case 8: 4 Vertical Piles

After analysing effect of orientation of pile for pile group consisting of two piles group, pile group consisting of four piles is considered. In this case the pile group consisting of four vertical piles is taken into consideration and displacement of pile group is recorded using dial gauge for each load increment and load displacement graph is plotted which is shown in fig

5.5. Comparison between case 8, 9 and 10 will be done to see which pile group offers better lateral load deflection resistance. On comparing this pile group with case 1 i.e., the case of single vertical pile it can be seen that at the lateral loading of 73.57N, pile group having four vertical batter pile offers 93.47% more lateral load deflection resistance as compared to single vertical pile, 57.98% more lateral displacement resistance than pile group having one vertical pile and one negative batter pile and 67.75% more lateral displacement resistance than pile group having one vertical pile and one positive batter pile.

5.1.9 Case 9: 2 Vertical and 2 Negative Batter Piles

In this group two negative batter piles are introduced in place of two vertical piles to see the effect of presence of negative batter pile on the lateral load resistance of pile group. Displacement is recorded for each load increment by the dial gauge and tabulated in table 5.4 and the graph between load and deflection is plotted for the same and shown in figure 5.5. From the figure 5.5 it can be seen that curve for case 9 is above curve for case 8 which means for same lateral loading case 9 which gives lesser deflection as compared to case 8. At 73.57 N lateral loading the pile group made by replacing two vertical piles with two negative batter pile gives 30.38% less deflection as compared to pile group having all four vertical pile , 62.84% gives less deflection as compared to pile group having two negative batter pile only and gives 86.62% less deflection as compared to single negative batter pile.

After seeing the effect of introducing negative batter pile in pile group the effect of introducing positive batter pile is done in case 10.

5.1.10 Case 10- 2 Vertical and 2 Positive

This case is considered for observing the effect of replacing two vertical piles with the two positive batter piles. The displacement reading is taken in similar manner with the help of dial gauge and graph between load and displacement is plotted and shown in fig 5.5. For the lateral load of 73.57 N the pile group consisting of 2 vertical and 2 positive batter pile showing displacement of 1.03 mm whereas in case of pile group having all vertical pile showing displacement of 0.79 mm whereas pile group in which two vertical pile are replaced by two negative batter pile showing displacement of only 0.55 mm which indicates that when negative batter piles introduced in pile group lateral displacement resistance of pile group increased whereas when positive batter piles are introduced in pile group lateral displacement resistance of pile group decreases. In case 10 at lateral load of 73.57 N 30.38% more deflection is measured as compared to pile group having all four vertical piles and 87.27% more deflection as compared to pile group consisting of two vertical and two negative batter pile.

Table 5.4: Load –Displacement readings of pile group having four piles

S.No.	**Lateral Load (N)**	**Deflection (mm)**		
		Case 8	**Case9**	**Case 10**
1	7.36	-	-	-
2	14.71	0.06	0.05	0.12
3	22.07	0.13	0.10	0.26
4	29.43	0.17	0.14	0.31
5	36.79	0.21	0.17	0.45
6	44.14	0.29	0.22	0.58
7	51.50	0.35	0.30	0.63
8	58.86	0.43	0.39	0.77
9	66.22	0.68	0.46	0.91
10	73.57	0.79	0.55	1.03

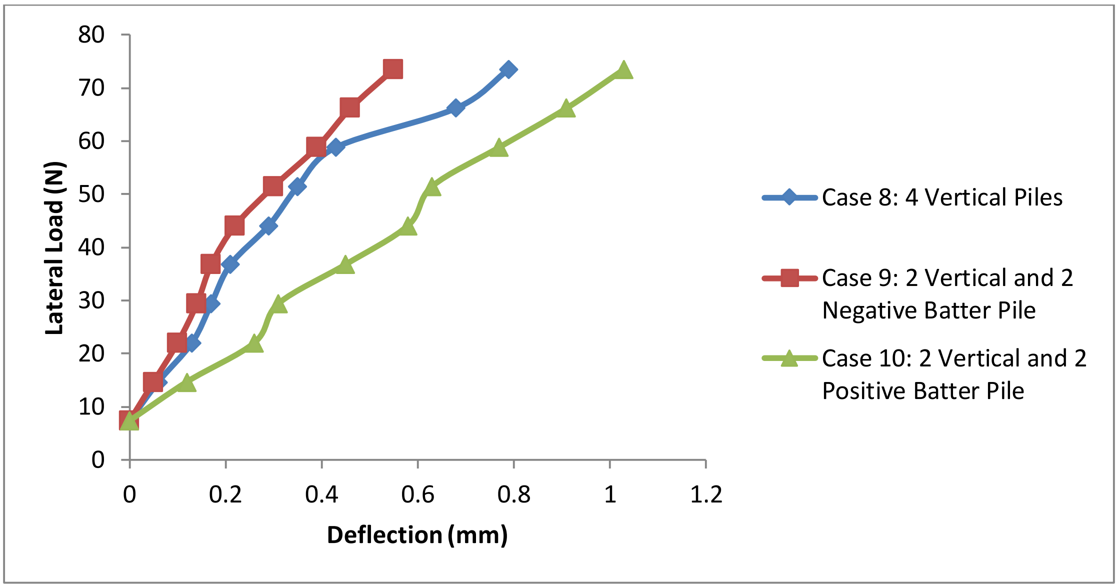

Fig 5.5: Load-Deflection curve comparison for case 8, 9 and 10.

For clear comparison between all the three piles group consisting of four piles refer load displacement curve which is shown in figure 5.5. From the figure it is clearly seen that curve for case 9 (red curve) above remaining two pile group which means it has greater lateral load displacement resistance whereas the pile group formed by introducing two positive batter pile i.e., case 10 curve (green curve) is lying under both of the curve which indicates that is has least lateral load displacement resistance. Thus it can be concluded that with the increase in number of negative batter pile lateral load displacement resistance increases.

Table 5.5: Load –Displacement readings of all the ten case

S.No.	Lateral Load (N)	Deflection (mm)									
		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
1	7.36	0.71	-	0.80	-	-	-	-	-	-	-
2	14.71	1.47	0.01	1.56	0.06	0.18	0.24	0.04	0.06	0.05	0.12
3	22.07	2.10	1.00	2.65	0.18	0.32	0.62	0.16	0.13	0.10	0.26
4	29.43	3.28	1.36	3.74	0.30	0.60	0.88	0.28	0.17	0.14	0.31
5	36.79	3.54	1.48	4.16	0.58	0.84	1.42	0.52	0.21	0.17	0.45
6	44.14	4.00	1.66	4.45	0.85	1.20	1.57	0.79	0.29	0.22	0.58
7	51.50	4.52	2.37	5.12	1.01	1.36	2.05	0.92	0.35	0.30	0.63
8	58.86	9.16	2.90	10.00	1.07	1.64	2.65	1.00	0.43	0.39	0.77
9	66.22	10.28	3.56	12.17	1.38	2.17	2.97	1.31	0.68	0.46	0.91
10	73.57	12.10	4.11	13.85	1.88	2.45	3.54	1.48	0.79	0.55	1.03

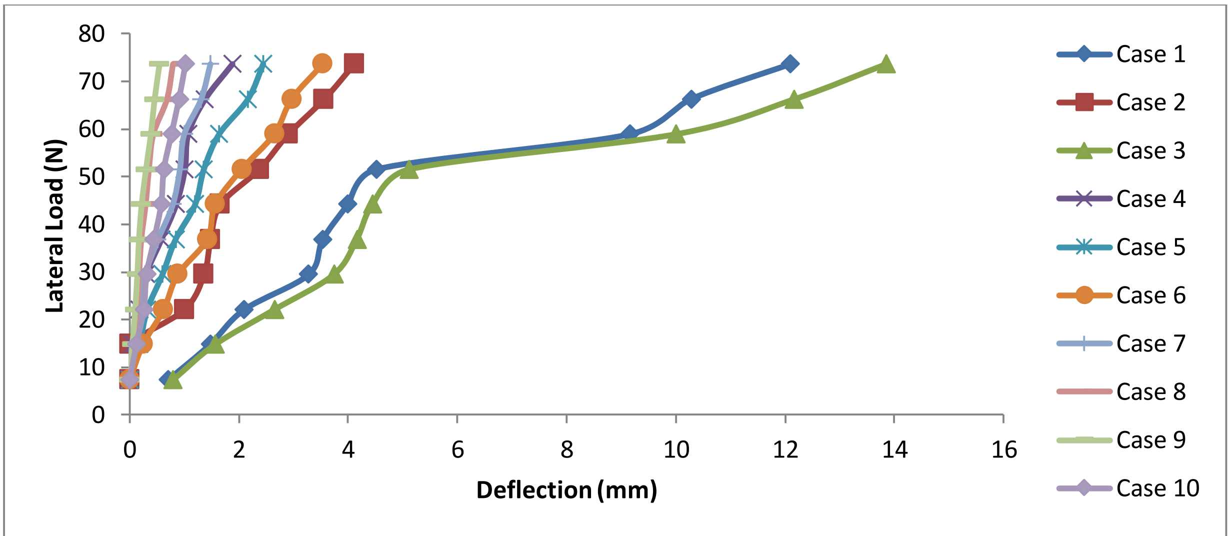

Fig 5.6: Load-Deflection curve comparison of all the ten cases.

Table 5.5 consist of load deflection data of all the ten cases for quick review and figure 5.6 consist of load deflection curve for all the ten cases for quick and ease in comparison between all the ten cases.

5.2 Effect of increasing batter angle

After observing effect of direction of inclination of pile with respect to lateral loading direction on the lateral load deflection resistance, the effect of batter angle on lateral load deflection resistance is considered. First of all effect of increasing batter angle in case of positive batter is considered by conducting experiment on piles having batter angle of +10^o, +15^o and +20^o.Load deflection reading for positive batter piles having different batter angles is tabulated in table 5.7. After observing effect of increasing batter angle on positive batter pile, effect of same is investigated on the negative batter pile by conducting lateral load test on negative batter piles have batter angle of -10^o,-15^{o}and -20^o.Load versus deflection readings of the negative batter piles having different batter angles is tabulated in table 5.8.

5.2.1 Vertical Pile (batter angle = 0^o)

To see the effect of batter angle on the lateral load deflection resistance of pile first of all batter pile having batter angle zero degree is driven into the sand tank and by increasing the load from 0.75 kg to 7.5kg (7.36 N to 73.57 N) with the increment of 0.75 kg deflection reading is noted down which are been recorded by dial gauge and tabulated in table 5.6.

Table 5.6: Load deflection readings for vertical pile (batter angle = 0)

S.No.	Lateral Load (N)	Deflection (mm)
1	7.36	0.71
2	14.71	1.47
3	22.07	2.1
4	29.43	3.28
5	36.79	3.54
6	44.14	4

7	51.5	4.52
8	58.86	9.16
9	66.22	10.28
10	73.57	12.1

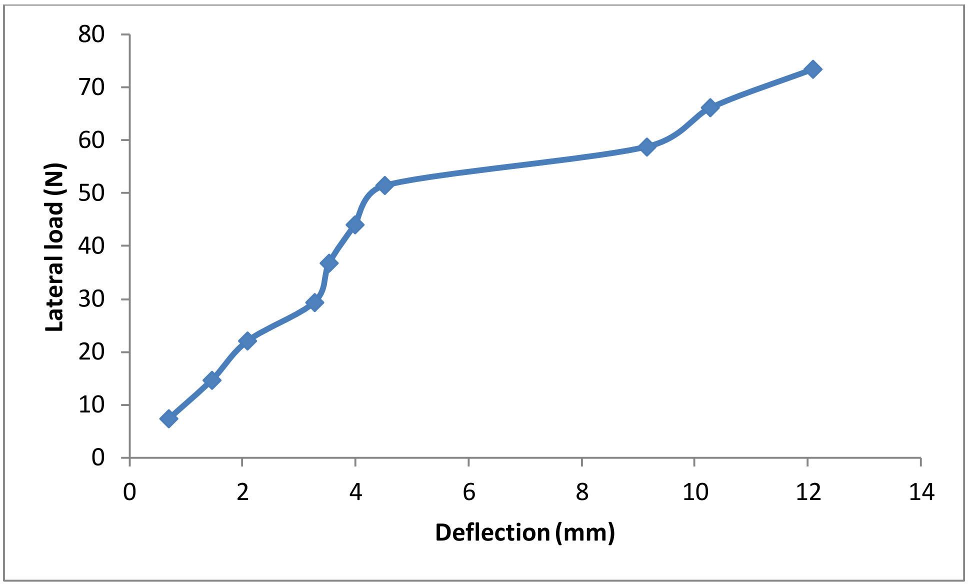

Fig 5.7: Lateral load versus deflection curve for pile having batter angle zero.

5.2.2 Positive batter pile

After noting down deflection readings for pile having zero batter angle on different lateral loadings the effect of increasing batter angle in case of positive batter pile is investigated. For this purpose load versus deflection readings were taken down for +10° and tabulated in table 5.7. Similarly, readings for +15° and +20° were tabulated in table 5.7. The reading of positive batter piles are compared with each other as well as with the vertical batter pile.

Table 5.7: Load deflection readings for positive batter pile (batter angle = 10, 15 and 20 degrees)

S.No.	**Lateral Load (N)**	**Deflection (mm)**		
		+10^0	**+15°**	**+20°**
1	7.36	0.64	0.8	1.26

2	14.71	1.52	1.58	2.15
3	22.07	2.27	2.65	3.66
4	29.43	3.58	3.74	4.1
5	36.79	3.9	4.16	5.2
6	44.14	4.25	4.45	5.68
7	51.5	4.96	5.12	6.64
8	58.86	9.66	10	12.1
9	66.22	11.37	12.17	13.44
10	73.57	12.74	13.85	14.82

It is clear from the table 5.7 that at the lateral loading of 73.57 N, the deflection in case of positive batter pile having +10^o batter angle is increased by 5.29% whereas in case of positive batter pile having +15^o and +20^o batter angle deflection increased by 14.46% and 22.48% respectively. For clear view refer to fig 5.8 which shows that each lateral load, deflection of positive batter pile having greater batter angle is higher.

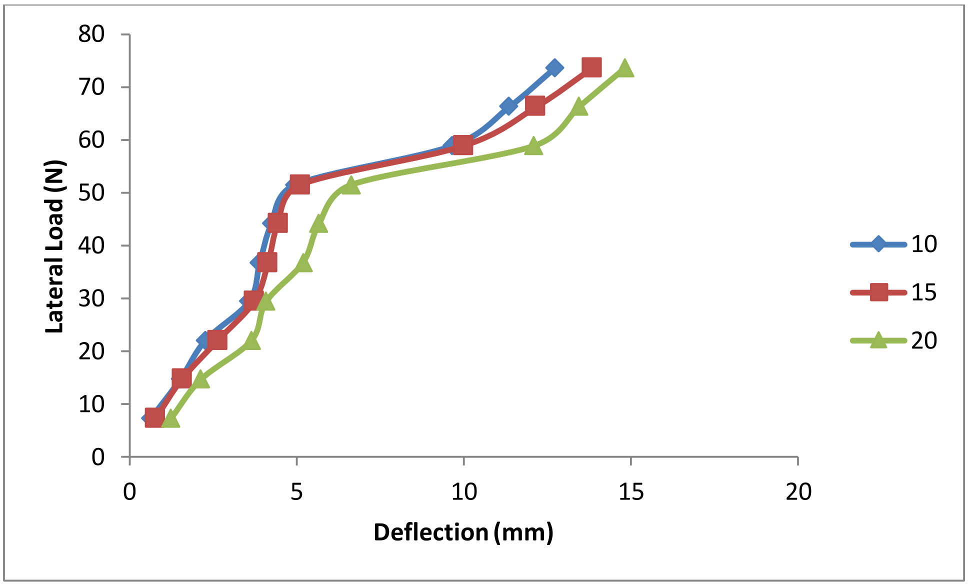

Fig. 5.8: Lateral load versus deflection curve for pile having batter angle +10, +15 and +20 degree.

5.2.3 Negative batter pile

After investigating effect of increasing batter angle in case of positive batter pile next step is to investigate effect of increasing batter angle on negative batter pile. For this purpose load versus deflection readings were taken down for -10^o and tabulated in table 5.8. Similarly, readings for -15^o and -20^o were tabulated in table 5.8. The reading of negative batter piles are compared with each other as well as with the vertical batter pile.

Table 5.8: Load deflection readings for negative batter pile (batter angle = 10, 15 and 20 degrees)

S.No.	Lateral Load (N)	Deflection (mm)		
		-10^0	**-15^o**	**-20^o**
1	7.36	0.01	-	-
2	14.71	0.36	0.01	-
3	22.07	1.75	1	0.42
4	29.43	2.4	1.36	0.96
5	36.79	2.62	1.48	1.2
6	44.14	2.84	1.66	1.48
7	51.5	3.15	2.37	2
8	58.86	4.58	2.9	2.36
9	66.22	5.85	3.56	2.95
10	73.57	6.6	4.11	3.44

It is clear from the table that at the lateral loading of 73.57 N, the deflection in case of negative batter pile having -10^o batter angle is decreased by 44.63% whereas in case of negative batter pile having -15^o and -20^o batter angle deflection decreased by 66.03% and 71.57% respectively. For clear view refer to fig 5.9 which shows that each lateral load, deflection of negative batter pile having greater batter angle is smaller i.e, -20° batter pile gives greater lateral load deflection resistance followed by -15° ,-10° and 0°.

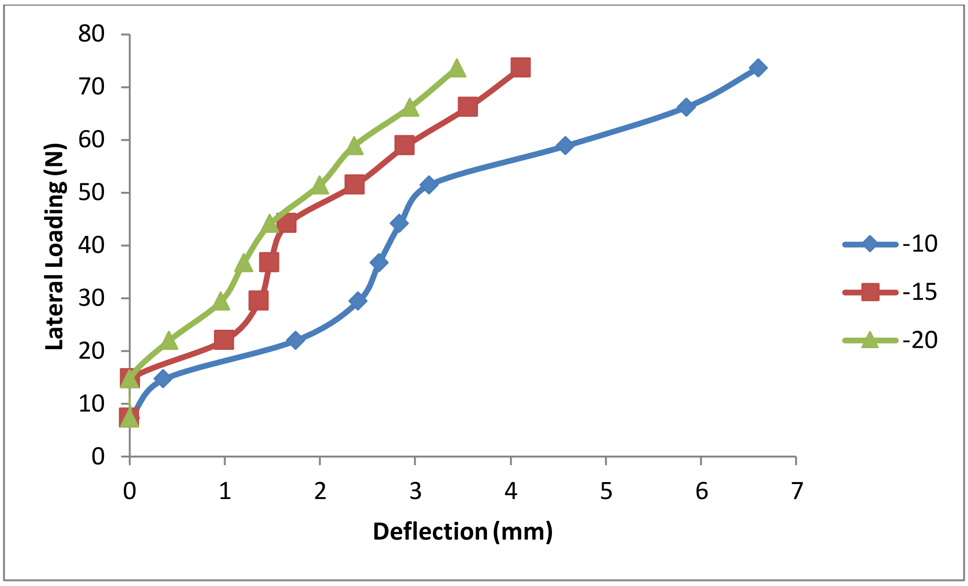

Fig. 5.9: Lateral load versus deflection curve for pile having batter angle -10,-15 and -20 degree.

Table 5.9 consist of load deflection data of all batter angles cases for quick review and figure 5.10 consist of load deflection curve for all batter angles for quick and ease in comparison between all cases.

Table 5.9: Load deflection readings for all pile (batter angle = -20,-15,-10, 0, +10, +15, +20, degrees)

S.No.	Lateral Load (N)	Deflection (mm)						
		+20°	+15°	+10°	0°	-10°	-15°	-20°
1	7.36	1.26	0.8	0.64	0.71	0.01	-	-
2	14.71	2.15	1.58	1.52	1.47	0.36	0.01	-
3	22.07	3.66	2.65	2.27	2.1	1.75	1	0.42
4	29.43	4.1	3.74	3.58	3.28	2.4	1.36	0.96
5	36.79	5.2	4.16	3.9	3.54	2.62	1.48	1.2
6	44.14	5.68	4.45	4.25	4	2.84	1.66	1.48
7	51.5	6.64	5.12	4.96	4.52	3.15	2.37	2

8	58.86	12.1	10	9.66	9.16	4.58	2.9	2.36
9	66.22	13.44	12.17	11.37	10.28	5.85	3.56	2.95
10	73.57	14.82	13.85	12.74	12.1	6.6	4.11	3.44

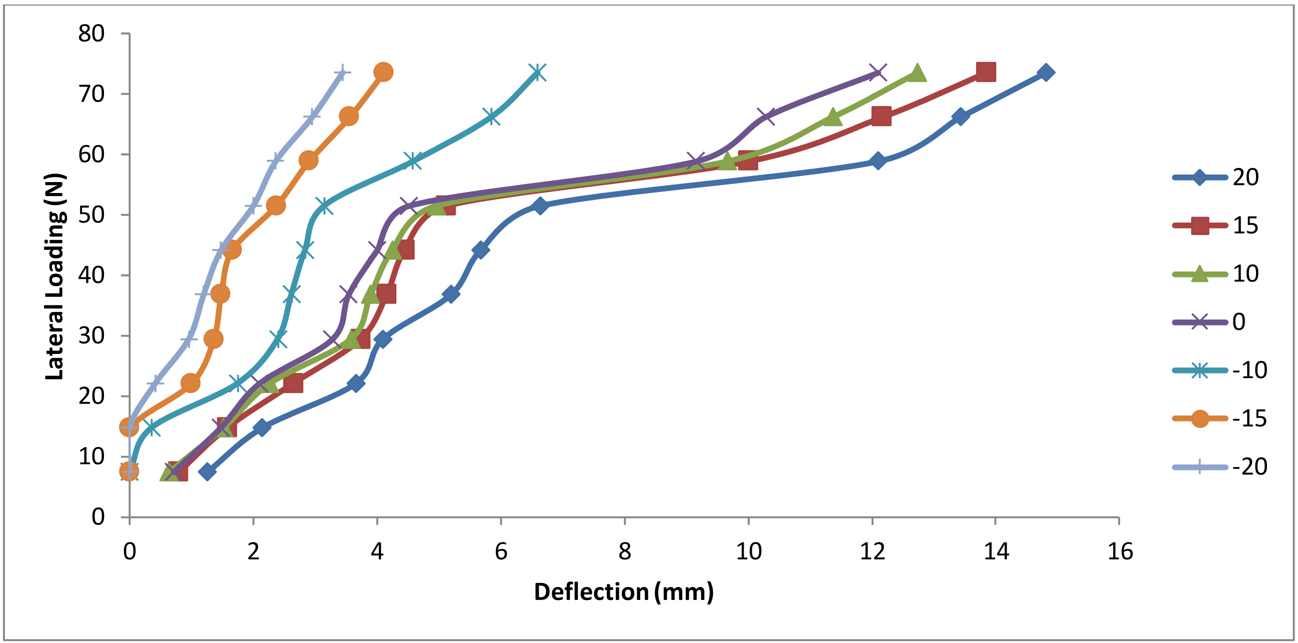

Fig 5.10: Comparison of load versus deflection curve for all pile (batter angle = -20,-15,-10, 0, +10, +15, +20, degrees)

5.3 Effect of Reloading

For investigating effect of inclination direction of pile and batter angle on the lateral load deflection resistance, effect of reloading is taken into consideration since lateral load does not act continuously. In this case load-deflection readings are recorded for vertical pile, positive batter pile and negative batter pile where batter angle is 15^{o} to see out of the three which pile is gives better lateral load deflection resistance due to reloading. In other words it can be said that following experimental studies is conducted to investigate that on which type of pile effect of reloading is least.

5.3.1 Vertical pile

To investigate reloading effect deflection reading is recorded for lateral load of 0.75 kg to 7.5 kg with each increment of 0.75 kg after loading unloading is carried out from 7.50 kg to 0.75

kg and corresponding dial gauge reading were recorded. Reloading is done in similar manner as loading and reading were tabulated in table 5.10.

Table 5.10: Load -deflection readings for loading and reloading in case of vertical pile.

S.No.	Lateral Load (N)	Deflection (mm)		
		Loading	Unloading	Reloading
1	7.36	0.71	0.85	0.85
2	14.71	1.47	1.5	1.81
3	22.07	2.1	2.26	2.72
4	29.43	3.28	3.35	3.5
5	36.79	3.54	3.81	4.44
6	44.14	4	4.22	4.78
7	51.5	4.52	4.85	5.11
8	58.86	9.16	9.37	10.44
9	66.22	10.28	10.52	11.86
10	73.57	12.1	12.1	13.52

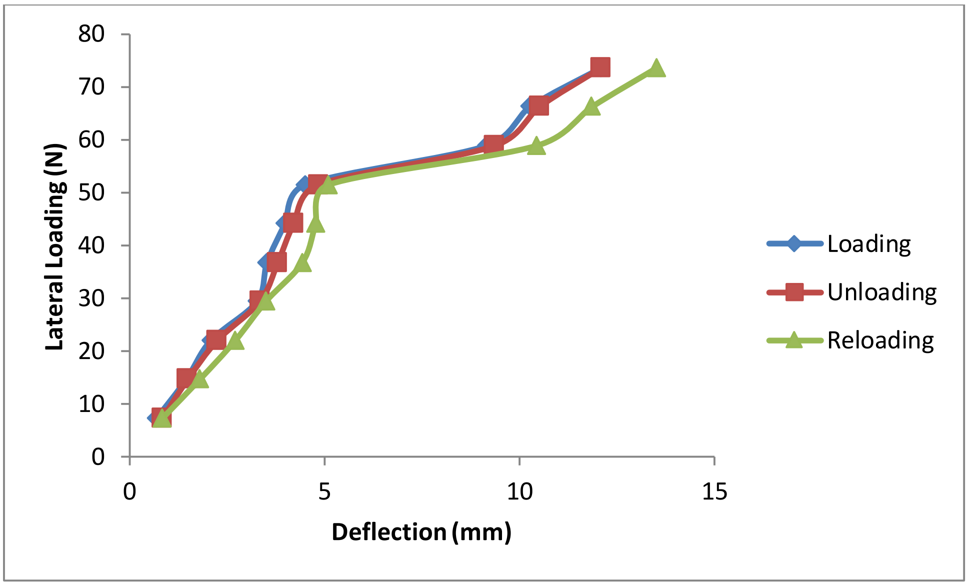

Fig. 5.11: Effect of reloading in case of vertical pile.

It can be seen from the table 5.10 at lateral loading of 73.57 N, deflection of vertical pile increase by 11.73% due to only 1 time reloading.

5.3.2 Positive batter pile (+15º)

In case of positive batter pile deflection readings are taken with the help of dial gauge for each load increment i.e., from 0.75 kg to 7.5 kg. After loading, unloading is done by removing weights in the same order as the loading was done and corresponding deflection reading were noted down. Reloading is done when unloading is completed and the readings are tabulated in table 5.11.

Table 5.11: Load -deflection readings for loading and reloading in case of positive batter pile.

S.No.	Lateral Load (N)	Deflection (mm)		
		Loading	Unloading	Reloading
1	7.36	0.8	0.94	0.94
2	14.71	1.58	1.72	2.42
3	22.07	2.65	2.88	3.78
4	29.43	3.74	3.92	4.91
5	36.79	4.16	4.35	5.8
6	44.14	4.45	4.6	6.88
7	51.5	5.12	5.44	8.45
8	58.86	10	10.35	11.52
9	66.22	12.17	12.26	13.2
10	73.57	13.85	13.85	16.43

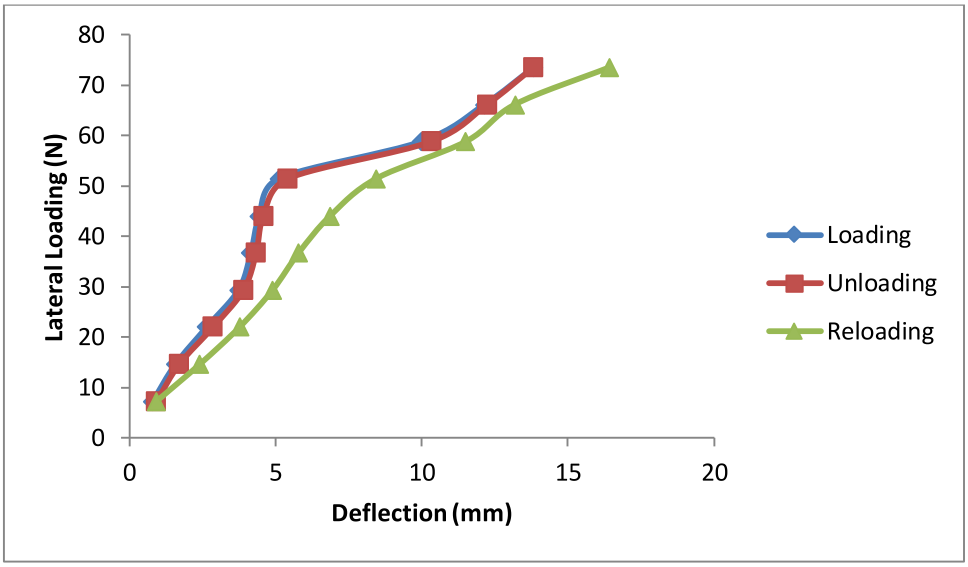

Fig. 5.12: Effect of reloading in case of positive batter pile.

From the table 5.11 it can be seen that at lateral loading of 73.57 N, deflection of Positive batter pile increase by 18.62% due to only 1 time reloading.

5.3.3 Negative batter pile (-15º)

In case of negative batter pile reading is taken in similar manner as in vertical pile for loading, unloading, reloading and tabulated in table 5.12.

Table 5.12: Load -deflection readings for loading and reloading in case of negative batter pile.

S.No.	Lateral Load (N)	Deflection (mm)		
		Loading	Unloading	Reloading
1	7.36	-	0.01	0.01
2	14.71	0.01	0.03	0.05
3	22.07	1	1.15	1.22
4	29.43	1.36	1.58	1.65
5	36.79	1.48	1.62	1.72
6	44.14	1.66	1.86	1.98
7	51.5	2.37	2.5	2.84
8	58.86	2.9	3.15	3.43
9	66.22	3.56	3.62	4
10	73.57	4.11	4.11	4.46

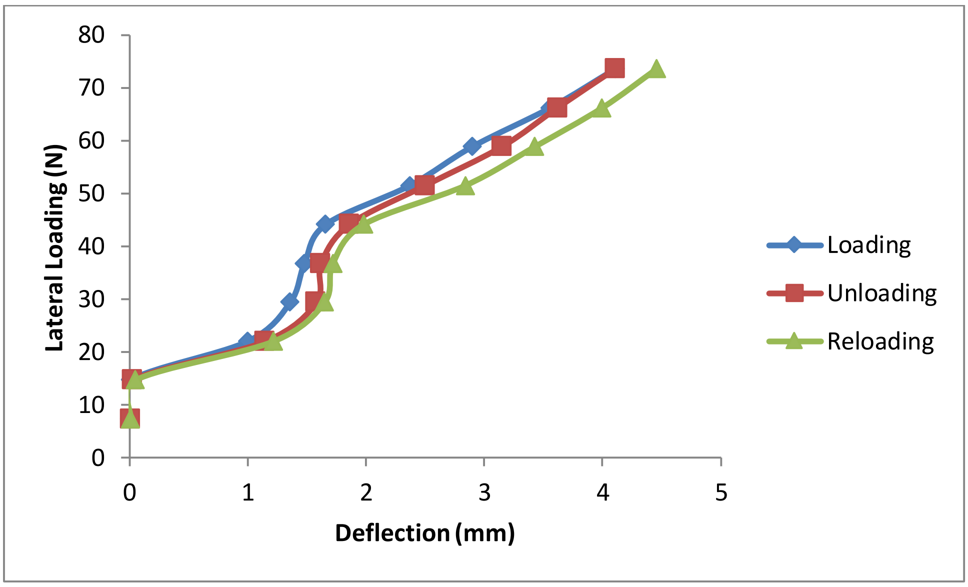

Fig. 5.13: Effect of reloading in case of negative batter pile.

From table 5.13 it can be seen that at lateral loading of 73.57 N, deflection of negative batter pile increase by 8.51% due to only 1 time reloading. By comparing reloading effect of all the three piles i.e., vertical pile, positive batter pile and negative batter pile it is clear that effect of reloading is maximum in case of positive batter pile and minimum in case of negative batter pile.

CHAPTER 6
CONCLUSIONS

The main objective of this dissertation work is to investigate the effect of orientation of pile on the lateral load deflection resistance. The need for research on pile and pile group due to inclination of pile under lateral loading is addressed by conducting experiments on model piles. Soil sample used is locally available sand which was found out to be poorly graded. Dimensions of pile were modelled using proper scaling laws. Boundary effect was also taken into consideration while fabricating set up. Experiments were conducted on different pile and pile groups subjected to lateral loading. The pile cap deflection was measured by dial gauge to obtain load deflection curves for all the cases and from the experimental study following conclusions were drawn:

1. Negative batter pile offers maximum resistance towards lateral load deflection whereas positive batter pile gives least lateral load deflection resistance.
2. By increasing in L/d ratio resistance of pile for lateral deflection increases.
3. Behaviour of pile groups containing batter pile mainly depends upon the orientation of batter pile in the group.
4. Pile group having both batter pile and vertical pile are more resistant to lateral displacement than pile group having vertical piles only.
5. Pile group having negative batter piles are more resistant to lateral displacement than the pile group having positive batter pile. Case 9 has the highest lateral load deflection resistance among all the ten cases.
6. Increase of batter angle in positive batter pile cause decrease of lateral load deflection resistance of positive batter pile.
7. Increase of batter angle in negative batter pile cause increase of lateral load deflection resistance of negative batter pile.
8. Deflection in pile having -20^o batter angle is least whereas pile having +20^o batter angle is most.
9. Increasing order of lateral load deflection resistance in pile is $+20^o < +15^o < +10^o < 0^o < -10^o < -15^o < -20^o$.
10. Reloading cause increase in deflection of pile due to re application of the same loading. Reloading affects the negative batter pile least whereas positive batter pile affects the most.

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