

## Experimental study on performance of laterally loaded plumb and battered piles in layered sand

Bushra S.Albusoda (Ph.D.)

Professor

College of Engineering - University of Baghdad  
dr.bushra\_albusoda@coeng.uobaghdad.edu.iq

Anmar F.Alsaddi.

Researcher

College of Engineering - University of Baghdad  
anmar.alsaadi@yahoo.com

### ABSTRACT

This study introduces a series of single and pile group model tests subjected to lateral loads in multilayered sand from Karbala, Iraq. The aim of this study is to investigate: the performance of the pile groups subjected to lateral loads; in which the pile batter inclination angle is changed; the effect of pile spacing (s/d) ratio, the influence of using different number of piles and pile group configuration. Results revealed that the performance of single negative (Reverse) Battered piles with inclination of 10° and 20° show a gain of 32% and 76 % in the ultimate lateral capacity over the regular ones. For pile groups, the use of a combination of regular, negative and positive battered piles in different angles of inclination within the same group shows a significant increase in the ultimate lateral load carrying capacity. Increasing the spacing between piles in groups of the same category shows an increase in the group efficiency, also changing the piles number within the group by using different patterns will influence the ultimate lateral resistance of the pile group.

**Key words:** Lateral resistance, single pile, pile group, Battered Piles, Regular Piles.

### دراسة مختبرية حول أداء الركائز المائلة و العمودية المحملة جانبيًا في تربة رملية متعددة الطبقات

أنمار فاضل جاسم  
باحث

كلية الهندسة – جامعة بغداد

ديبشري سهيل زيار  
أستاذ مساعد

كلية الهندسة – جامعة بغداد

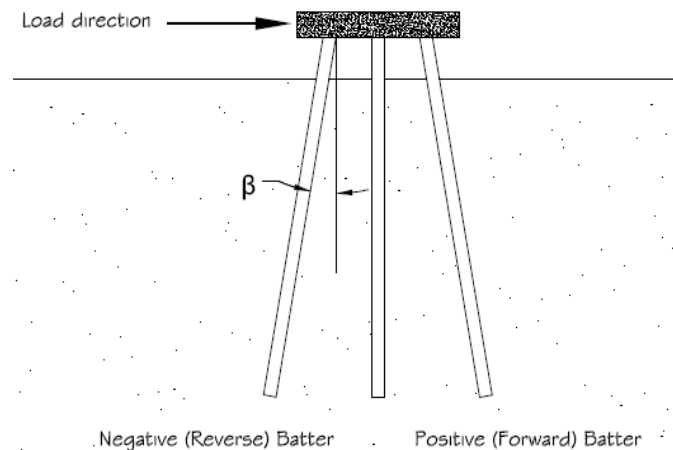
### الخلاصة

تقدم الدراسة الحالية بحثًا حول تأثير استخدام الركائز المائلة و المعرضة الى أحمال جانبية بشكل مفرد او ضمن مجموعات الركائز مختلفة الأنماط و الأعداد ، بزوايا ميلان مختلفة و بمسافات مختلفة في طبقات من التربة الرملية لمحافظة كربلاء، العراق . حيث تم دراسة تأثير العوامل انفة الذكر على سلوك الركائز باستخدام زوايا ميلان مختلفة للركائز او خليط من الركائز العمودية و المائلة ضمن نفس المجموعة و مقارنتها مع مثيلاتها من الركائز الأعتيادية (العمودية) . اظهرت النتائج ازدياد قابلية التحمل الجانبية للركائز المفردة و المائلة بزوايا سالبة بمقدار 32% و 76% بالمقارنة مع الركائز المفردة العمودية. من جانب اخر اظهرت مجموعات الركائز الحاوية على ركائز مائلة بزوايا مختلفة زيادة في قابلية التحمل الجانبية بشكل مضطرد، ان استخدام نمط توزيع الركائز بالشكل (G5) (نمط التوزيع الحاوي على 5 ركائز ضمن المجموعة) و بعدد ركائز اكثر ادى الى زيادة قابلية التحمل الجانبية للركائز و بشكل ملحوظ، مع ملاحظة ان زيادة المسافات بين ركائز المجموعة الواحدة سيؤدي الى زيادة قابلية التحمل الجانبية ايضا .

**الكلمات الرئيسية:** قابلية التحمل الجانبية ، الركائز المفردة، مجموعات الركائز، الركائز المائلة، الركائز العمودية .

## 1. INTRODUCTION

When regular or plumb pile groups do not provide sufficient lateral resistance, the piles can be battered in order to mobilize some of the axial capacity to resist lateral loads. Batter pile or inclined pile are generally classified into two types based on the loading direction. The pile which is battered toward the loading direction is negative batter or reverse batter pile, whereas, the pile battered against the loading direction is positive or forward batter pile as shown in **Plate 1**.



**Plate 1.** Categorization of Batter piles.

One of the first recorded laterally loaded battered piles tests were conducted by **Tschebotariofi, 1953** in which the capacity of a single pile battered 15 degrees in tension and compression and plumb was measured. The results showed that the lateral capacity of a pile battered in compression was much smaller than the capacity of a pile battered in tension. The tension pile had a capacity that is 50% to 70% higher than the capacity of the compression pile. The tension battered pile was also higher than the plumb pile which itself was higher than the compression pile.

**Shang, 1994** performed lateral load tests on 3 by 3 batter pile groups in medium dense ( $D_r = 55\%$ ) and loose ( $D_r = 33\%$ ) sand. A series of plumb pile tests were conducted for comparison. The pile spacing used was 3D and 5D. The results were as follows: 1. The groups in the higher density sample had significantly higher lateral resistance than did the looser samples. At 3 inches, lateral deflection the 3D pile group has a 57% higher lateral capacity in a 55% than in a 33% relative density sample. Also at 5D spacing, the pile groups in the 55% relative density samples had a 48% higher lateral capacity than the ones in the 33% relative density sample. 2. In both dense and loose samples, the pile groups arranged in 5D spacing had a higher lateral load capacity than the ones arranged in 3D spacing. This was attributed to the reduction of overlapping passive shear zones between piles with increasing distance.

Based on a centrifugal test on laterally loaded single battered piles embedded in sand, **Zhang et al., 1999** inferred that the effect of pile inclination on the lateral resistance is more effective in the dense sand and the lateral resistance of pile increases with the increment of the inclination of reversed or negative battered pile, whereas the lateral resistance decreases with the increment of inclination of forwarded or positive battered pile. **Rajashree, and Sitharam, 2001** performed a non-linear static analysis for both positive and negative batter piles at different angles ( $10^\circ$ - $30^\circ$  inclination) and observed that the lateral deflection predicted at the ground line for a pile in positive batter is more than for vertical pile and less than for a negative batter pile.

**Sheikhabaei, and Vafaeian, 2009** conducted dynamic response of concrete batter pile group under seismic excitation through finite element modeling and concluded that the increment of either batter inclination or center-to-center spacing reduces pile displacement, bending moment and Shear force.

**Albusoda, and Al-Mashhadany, 2014** carried out a series of tests to study effect of vertical allowable load and ( $l/d$ ) ratio on the torsional behavior of piles, it was concluded that increasing number of piles and ( $l/d$ ) ratio leads to increase the torsional capacity of pile group.

**Albusoda, and Al-Mashhadany, 2015** investigated the response of pile groups to eccentric lateral load, it was concluded that the torsional capacity of pile group will increase as the allowable vertical

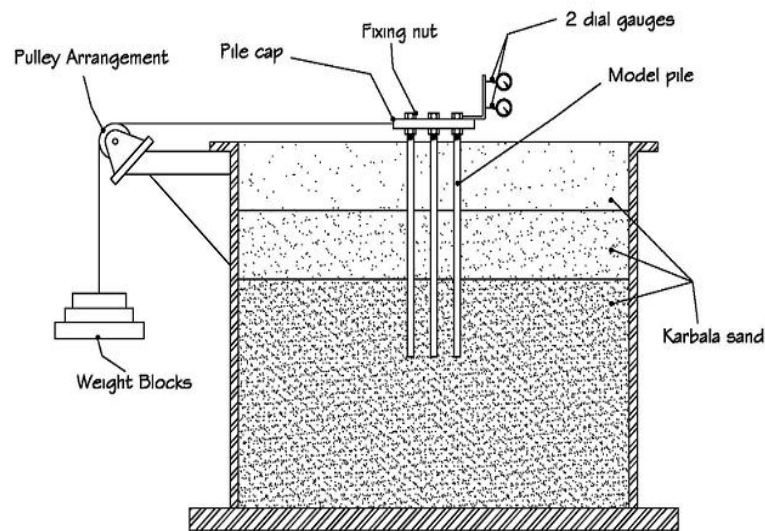
load increases. In addition, the increase in number of piles and L/D ratio leads to increase in the torsional capacity of pile groups.

**Albusoda, and Alsaddi, 2017** investigated the performance of single and pile groups subjected to lateral loads, it was concluded that the lateral performance of piles increases due to the installation of fin extensions. Increasing the piles spacing ratio and number of piles within the group will lead to an improvement in the lateral performance of the group.

The objective of this research is to evaluate the performance of different piles as single or as group to assess the improvement in the ultimate lateral load carrying capacities, such improvement is a substantial goal in designing an economical foundation for structures enduring large lateral loads.

## 2. EXPERIMENTAL SETUP

A setup was fabricated for conducting the experimental tests of this research; a schematic diagram of the test setup is shown in **Plate 2**.



**Plate 2.** Side view of the testing container.

### 2.1. Testing Container

Experimental investigations have been conducted in a testing tank that was made of mild steel consisting of four detachable sides of 4 mm thickness plates and a base of 6 mm thick plate, the tank was fabricated with internal dimensions of 1000 mm width, 1000 mm length and 800 mm height. The testing container was equipped with a square small door that can be used as a draining port of the sand inside the tank after completing the tests, the inner faces of the tank graduated into eight equal layers of 100 mm marked with two different colors to facilitate the sand bed preparation.

### 2.2. Raining System

A raining system was manufactured to obtain a relatively homogeneous sand beds depending on the discharge rate and height, the raining system consisted of a frame and a hopper, a curtain miner sand hopper was made of steel and has a dimension of (980 × 200 × 300) mm equipped with two strips opening of (5) mm each to discharge the rained sand, the sand hopper is attached to the sliding beam of the raining frame using two height adjustable shafts. **Plate 3** shows the raining hopper.



**Plate 3.** Curtain miner raining hopper.

### 2.3. Loading Frame

A pulley arrangement was used as lateral loading frame attached to the side wall of the steel box in which a steel wire is passed through to hold a static weight at one end while the other end is connected to the pile cap, as shown in **Plates (2) and (4)**.

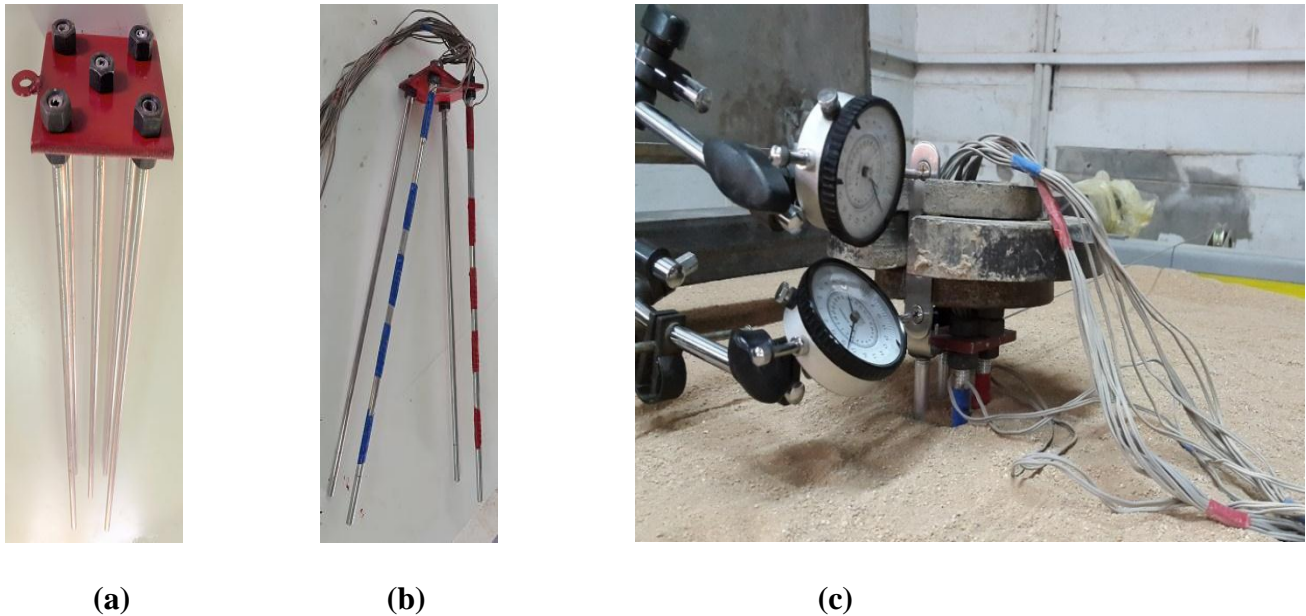
### 2.4. Model Pile and Pile Cap

The model piles used in the current study were fabricated from aluminum alloy tubing with a closed end having a total length of (500 mm), an outer diameter of (10 mm), and wall thickness of (1mm). The slenderness ratio ( $L/d$ ) of the model piles is 50 while the embedded depth used for the tests was (450 mm). **Plate (4.a)** and **(4.b)** show model pile groups used in this study. The pile rigidity was also related to the dimensionless embedment length  $l_p$  for short and long piles.

**Broms, 1964** introduced a coefficient that is calculated from:

$$N = \frac{\sqrt[5]{n_h}}{\sqrt{E_p * I_p}} \quad (1)$$

Where  $E_p$  is the modulus of elasticity of the pile material ( $69.4 \times 10^6$  kN/m<sup>2</sup>),  $I_p$  is moment of inertia of the pile cross section ( $2.898 \times 10^{-10}$  m<sup>4</sup>), and  $n_h$  is the constant of subgrade reaction at the pile tip. According to **Terzaghi, 1944**, the ranges of values for the coefficient ( $n_h$ ) appearing in equation (1) are (2.2, 6.6 and 17.6) MN/m<sup>3</sup> for (loose, medium and dense) dry sand, respectively. The dimensionless embedment length ( $N l_p$ ) has to be less than 2 to be considered as a short rigid pile and greater than 4 to behave as a long elastic pile. Based on this criterion, the model pile used in this study was fabricated to satisfy the flexible condition. Pile caps were made of (6 mm) steel plates in which the cap will behave as rigid element compared to the aluminum model piles since the flexural rigidity ( $EI$ ) of the steel cap is much larger than that for the aluminum pile, an extension was welded to the edge center of the cap that allows a steel tension wire to be attached.



**Plate 4.** (a) Vertical pile group (b) Batter pile group (c) Testing setup view.

### 3. SOIL PROPERTIES AND SAND BED PREPARATION

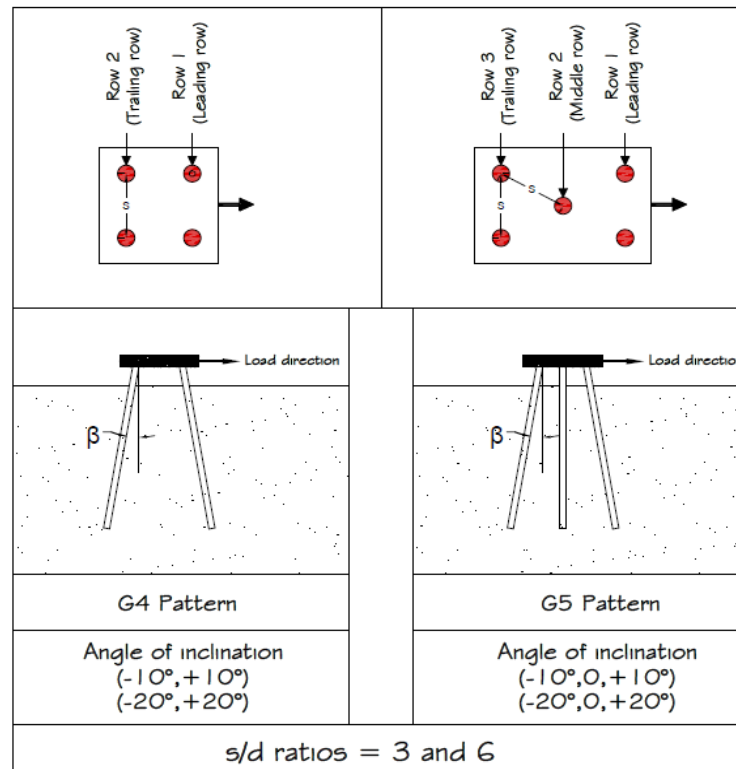
Dry commercially available sand was used in this study from Karbala, Iraq. The sample sand was classified as (SP) according to (Unified Soil Classification System). The mean grain size ( $D_{50}$ ) and the uniformity coefficient ( $C_u$ ) of the sample sand was found to be (0.4 mm) and (2.56) respectively. **Fig.1** shows the gradation curve for the sand. The maximum and minimum dry unit weights were (17.385 and 14.365) ( $\text{kN/m}^3$ ), respectively. All physical properties tests of the sand were performed in accordance with the ASTM standards.

The need for sand porosity control between associated minimum and maximum values led to the development of several techniques by researchers such as vibration, tamping, and pulverization to reconstruct sand samples in the laboratory, sand raining (pulverization) is the most familiar technique and its widely used for preparing large, more homogeneous and repeatable sand beds of different densities in geotechnical models that simulate the in-situ sand deposition. Raining calibration was performed to obtain a relationship between the sand deposition elevation and the ( $D_r$  %). In order to reconstruct the sand bed at three different relative densities, the sand was allowed to fall freely from a height of (500, 340 and 120 mm) to obtain a ( $D_r$  % = 70 %, 50 % and 32%) from bottom to top of the testing tank. The estimated angles of Friction ( $\phi$ ) using Direct Shear Test were ( $42^\circ$ ,  $38^\circ$  and  $34^\circ$ ) for (dense, medium and loose) states respectively. **Table 1** shows a summary of the sample sand physical properties.

### 4. TESTING PROCEDURE

Different pile group configurations with specific angle of inclinations and in different spacing have been tested in this experimental study, the center to center spacing were  $3d$  and  $6d$  for both plumb piles and Battered piles. Two different angles of inclination were used ( $10^\circ$  and  $20^\circ$ ) for the battered piles. **Plate 5** shows the side view of single and group battered piles used in this study.





**Plate 5.** Pile group patterns and side view of battered piles prototypes.

At the beginning of the test, the sand was poured from a specific height using the curtain miner sand hopper until the pile base level reached the piles were installed using a temporary metal mesh fixed to the container sides and plastic bands acting as a clamp to fix the pile in vertical or inclined alignment. To eliminate any boundary effect between the piles and container sides the piles were placed at least 10 D distance from each side of the box and 30 D from the base. Raining process was then resumed until the sand reached the top of the container to achieve a level of 50 mm below the pile head. The pile cap was then installed. Two dial gauges were mounted on a rigid steel L-shaped extension connected to the pile cap, these dial gauges were used to measure the horizontal displacement at pile portion above the ground line. Then the piles were loaded incrementally until failure occurred. The single and pile groups tested in this study are summarized in **Table 2**.

## 5. RESULTS AND DISCUSSIONS

A series of 15 experimental tests had been conducted to study the influence of pile spacing ratio ( $s/d$ ), number of piles within a group, group pattern and the angle of inclination on the pile lateral resistance and group efficiency. The group efficiency ( $\eta$ ) can be expressed as the variation of the pile group resistance at a given deflection. According to **Table 2**, battered pile groups may consist of negative, positive and vertical piles,

Pile head lateral load and lateral displacement curves for regular piles and battered piles are obtained from the experimental tests and are shown in **Fig. 2**. Different researchers introduce through their studies different assumptions on the interpretation of the ultimate lateral resistance of piles. Many assumptions are based on the excessive lateral displacement or pile rotation **Hu, et al., 2006. Prasad, and Chari, 1999** stated that the point where the load - displacement curve becomes linear or substantially linear is considered as the ultimate lateral capacity of pile. According to **Peng et al., 2004**, the lateral load corresponds to 10% displacement of pile diameter is considered as the failure load. In the present study and for the purpose of studying the influence of different factors and

conditions on the ultimate lateral capacity of piles, the load corresponding to 20% displacement of pile diameter is considered as the failure load.

### 5.1 Angle of Inclination Effect on Piles Performance

Increasing the angle of inclination for single piles in reverse direction shows a significant increase in the ultimate lateral capacity the gain was (32%) and (46%) for piles inclined in tension (reverse batter) on  $10^\circ$  and  $20^\circ$  respectively. **Fig. 2** shows the load versus settlement for single piles. For pile groups (G4S3) and (G5S3), the graphs show a gain in ultimate lateral capacities of (30%) and (38%) respectively for inclination angles of  $10^\circ$ . An increase of (47%) and (53%) for inclination angle of  $20^\circ$  is shown. Similarly the ultimate lateral capacities of (G4S6) and (G5S6) pile groups show a gain of (31%) and (50%) respectively for  $10^\circ$  inclination and (40%) and (79%) for  $20^\circ$  inclination over the vertical ones. These results revealed that the pile group's lateral capacity will increase upon using battered piles in spite of using the piles in both negative and positive directions within the same group. The general performance trend of the groups were in good agreement with was shown by **Karsan et al., 2011** in which pile groups with different inclination of (positive and negative) within the same group (0, 0, +10) to (0, 0, +30) and (-10, 00, +10) to (-30, 0, +30) offer (40-55%) more resistance as compared to vertical pile group.

### 5.2 Effect of Pile Spacing on the Group Ultimate Lateral Capacity

Results of studying the influence of changing the spacing of pile groups lies under the same category and pattern revealed that changing the pile spacing ratio (s/d) from 3 to 6 has a considerable effect on increasing the ultimate lateral load carrying capacity of pile group. **Fig. 3** shows the ultimate lateral capacity versus pile spacing. The ultimate lateral resistance of vertical type (G4S6) increases with (26%) more than that for the (G4S3), for the (G5S6) the gain in lateral load carrying capacity was about (11%). On the other hand, the battered piles groups (G4S6) show an increase of (27%) and (20%) over the (G4S3) for inclination angle of ( $10^\circ$ ) and ( $20^\circ$ ) respectively, similarly the (G5S6) ultimate lateral capacity shows an increase of (20%) and (30%) over the (G5S3). This reduction observed in the lateral performance of pile groups as the spacing ratio 6 to 3 can be attributed to the group interaction effects. When each pile in group pushes against the soil in front of it, creating a shear zone in the soil, these shear zones begin to enlarge and overlap as the lateral load increases. More overlapping occurs if the piles are spaced very close to each other in both rows and columns. All of these "group interaction effects" result in less lateral resistance per pile. "Edge effects" is used to describe the effects of overlapping zones of influence occurring between two piles in the same row, and when overlapping occurs between piles in different rows it is known as "shadowing effects".

### 5.3 Effect of Group Pattern on the Ultimate Lateral Capacity

The effect of increasing the number of piles on the lateral group efficiency is studied using two types of pile group configuration. The G5 pattern shows a significant influence on increasing the ultimate lateral capacity of the piles in comparison to the G4 pattern. For vertical piles comparing pile groups with the same (s/d) ratio (G4S3) group with (G5S3) and (G4S6) with (G5S6), revealed an increase of (40%) and (22%) respectively, while for battered piles the results show a gain of (48%) and (30%) for comparing (G4S3) group with (G5S3) and (G4S6) with (G5S6) respectively for an inclination angle of ( $10^\circ$ ) and a gain of (45%) and (56%) for groups with ( $20^\circ$ ) pile inclination. These results are introduced in **Fig.4**.



## 6. CONCLUSIONS

A series of laterally loaded laboratory model piles tests were carried out to investigate the influence of pile spacing, effect of using battered piles and using different patterns of pile groups on the ultimate lateral capacity. The following conclusions are drawn from the experimental works:

- 1- The lateral resistance of single piles increases with (32%) and (46%), upon using piles with reverse batter angle of ( $10^\circ$ ) and ( $20^\circ$ ) respectively. While for pile groups the ultimate lateral resistance were in gradual increase, the largest increase in the ultimate lateral resistance were recorded for (G4S6) and (G5S6) pile groups in which the gain recorded was (31%) and (50%) for  $10^\circ$  inclination and (40%) and (79%) for  $20^\circ$  inclination over the vertical ones.
- 2- Increasing the pile spacing ratio (s/d) from 3 to 6 within a group shows an increase in the lateral load carrying capacity of pile groups.
- 3- Increasing the number of piles within the group by using the G5 pattern will lead to a gain in the lateral load resistance of pile groups

## 7. REFERENCES

- Albusoda, bushra S. and Al-mashhadany Omar y.,2014. *Effect of allowable vertical load and length/diameter Ratio (L/D) on behavior of pile group subjected to torsion*, University of Baghdad, journal of engineering, vol 20 (12).
- Albusoda, bushra S. and Al-mashhadany Omar y.,2015. *Response of Piles Group Subjected to Eccentric Lateral Load*, AARU journal, vol 2 (22).
- Albusoda, bushra S. and Alsaddi, Anmar F.,2017. *Experimental study on performance of laterally loaded plumb and finned piles in layered sand*, ARJ journal, Vol. 3, Issue, 1, pp. 32-39.
- Broms, 1964. *The Lateral Resistance of Piles in Cohesionless Soils*, J. Soil Mech. Found.Div., ASCE, Vol. 90, No. SM3, May 1964b, pp. 123-156.
- Hu, Z., McVay, M., Bloomquist, D., Herrera, R., and Lai, P., 2006. *Influence of torque on lateral capacity of drilled shafts in sands*. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 132 (4), 456-464.
- Karsan R. Hirani and A. K. Verma, 2011. *Lateral load carrying capacity of model pile groups*.National Conference on Recent Trends in Engineering & Technology.
- Peng, J., Rouainia, M., Clarke, B., Allan, P., and Irvine, J., 2004. *Lateral resistance of finned piles established from model tests*. Beirut, CFMS, Lebanon., In Proceedings of the International Conference on Geotechnical Engineering, pp. 565–571.
- Prasad, Y.V.S.N., and Chari, T.R., 1999. *Lateral capacity of model rigid piles in cohesionless soils*.Soils and Foundations 39((2)): 21-29 .
- Rajashree, S. S, and Sitharam G.T. , 2001. *Nonlinear finite-element modeling of batter piles under lateral load*. Journal of Geotechnical and Geoenvironmental Engineering., vol 127 (7), pp: 604-612.
- Shang, T.-I., 1994. *Analysis of Laterally Loaded Piles in Sand* .Master's thesis,University of Florida.

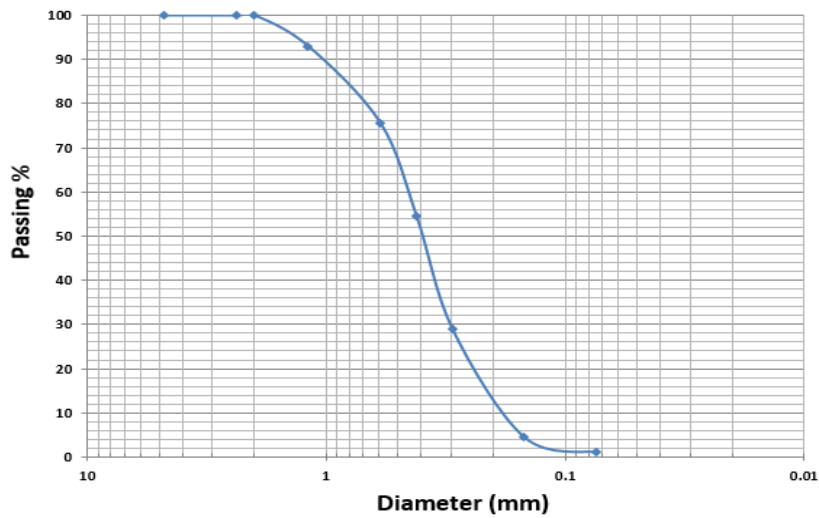




- Sheikhabaiei, A., and Vafaeian. M ., 2009. *Dynamic study of batter pile groups under seismic excitations through finite element method*. World Academy of Science, Engineering and Technology, pp:51-57.
- Terzaghi, K., 1944. *Theoretical Soil Mechanics*. New York.: Wiley.
- Tschebotariofl G.P, T., 1953. *The Resistance to Lateral Loading of Single Piles and of Pile Groups, Symposium on Lateral Load Tests on Piles*. Philadelphia,Pennsylvania: American Society of Testing Materials, No.154, pp. 38-48.
- Zhang, L., McVay, M.C., Han, J. H.,Lai, P. W. , 1999. *Centrifuge modeling of laterally loaded single battered piles in sand*. s.l.:Candian Geotechnical Journa., voll 36(6): 561-575.

## NOMENCLATURE

ASTM	American society for testing and materials
$C_u$	coefficient of uniformity
$C_c$	coefficient of curvature
$D_{10}, D_{30}, D_{60}$	particle sizes corresponding to 10%, 30%, and 60%
$D$	pile diameter
$D_r$	relative density
$G_s$	specific gravity
$EI$	pile flexural rigidity
$N$	broms coefficient
$\eta$	pile group efficiency
$s/d$	pile spacing ratio
$l/d$	slenderness ratio of pile
$l_p$	embedment depth of pile
$I_p$	moment of inertia of pile cross section.
$n_h$	coefficient of horizontal subgrade reaction.
$\emptyset$	angle of internal friction for sand
$\gamma_d \max$	maximum dry density
$\gamma_d \min$	minimum dry density



**Figure 1.** Karbala sand gradation curve.

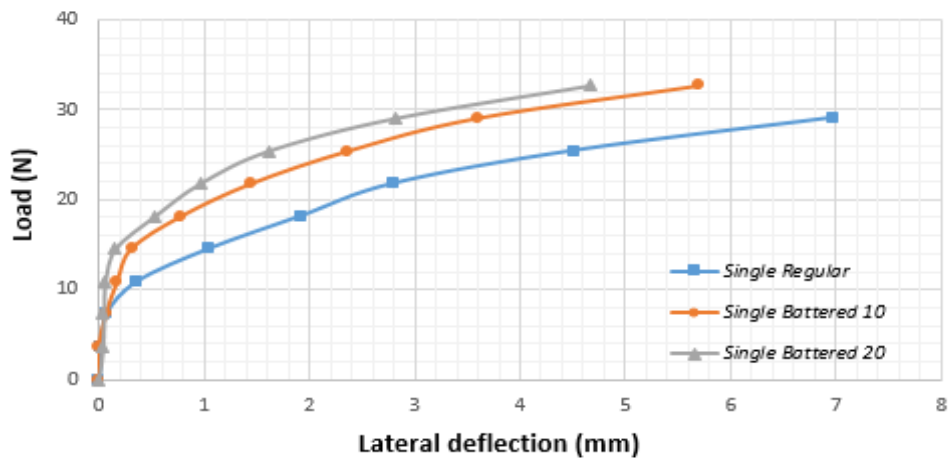
**Table 1.** Sand physical properties.

Soil index properties	values
Specific gravity (GS)	2.68
Soil Classification (USCS)	SP
$C_u$	2.56
$C_c$	1.16
$D_{10}$ (mm)	0.18
$D_{30}$ (mm)	0.31
$D_{50}$ (mm)	0.40
$D_{60}$ (mm)	0.46
Maximum dry unit weight (kN/m <sup>3</sup> )	17.385
Minimum dry unit weight (kN/m <sup>3</sup> )	14.365
Maximum void ratio	0.83
Minimum void ratio	0.51

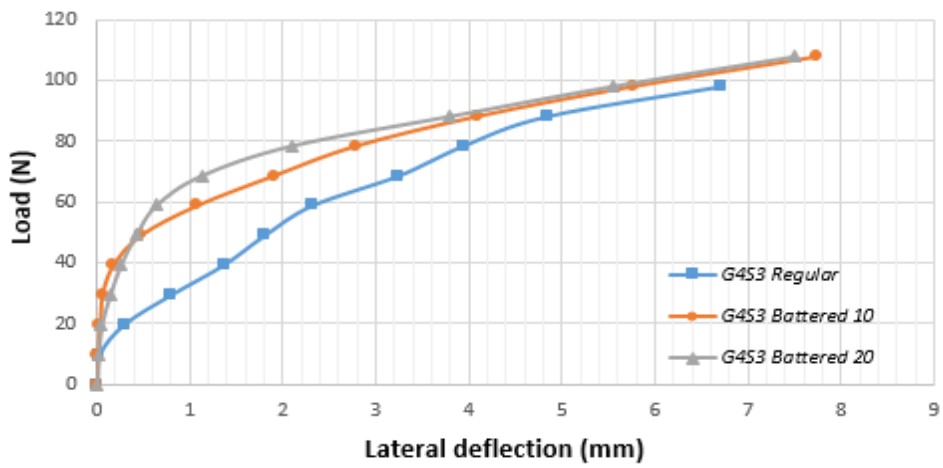
**Table 2.** Summary of experimental tests

Vertical piles (5 Tests)	Battered Piles (10 Tests)	
	Angle of inclination (leading row, trailing row1, trailing row2)	
Single	Single	(-10°) and (-20°)
G4S3	G4S3	(-10°,10°) and (-20°,20°)
G4S6	G4S6	(-10°,10°) and (-20°,20°)
G5S3	G5S3	(-10°,0°,10°) and (-20°,0°,20°)
G5S6	G5S6	(-10°,0°,10°) and (-20°,0°,20°)

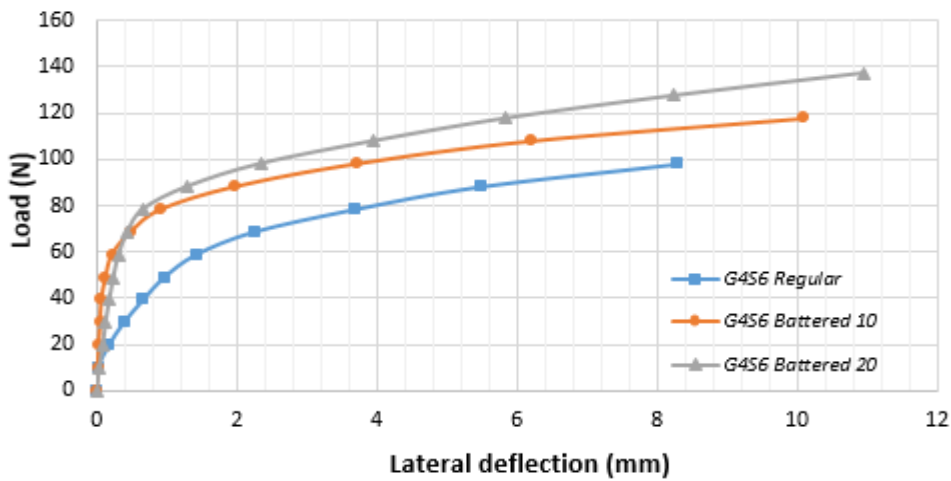
**Note:** Example of symbolic name of pile groups: (G4S3 = Group with 4 piles pattern and  $s/d = 3$ )



(a)

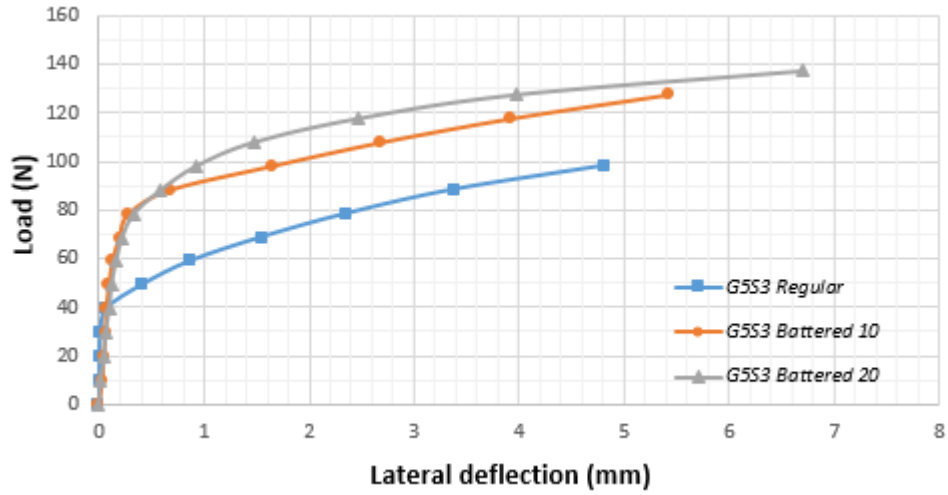


(b)

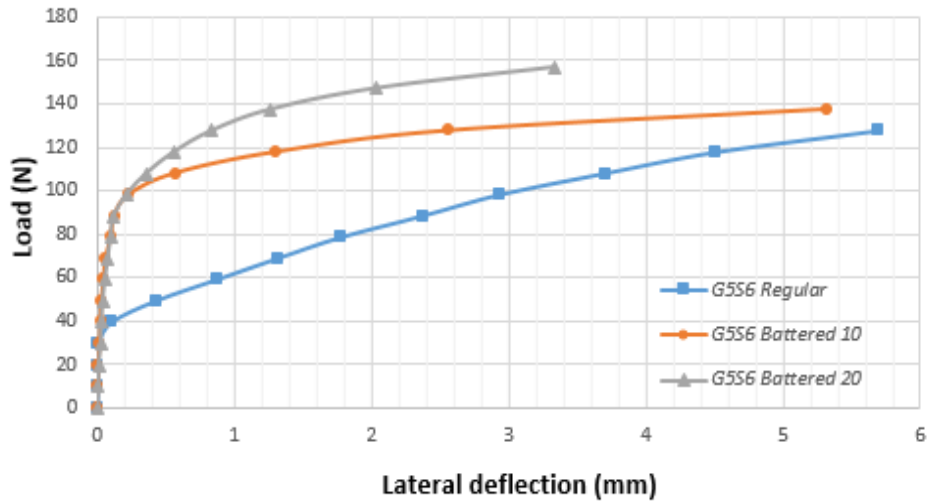


(c)

**Figure 2.** Ultimate lateral load versus lateral deflection for Battered and regular piles (a) Single (b) G4S3 (c) G4S6 (d) G5S3 (e) G5S6.



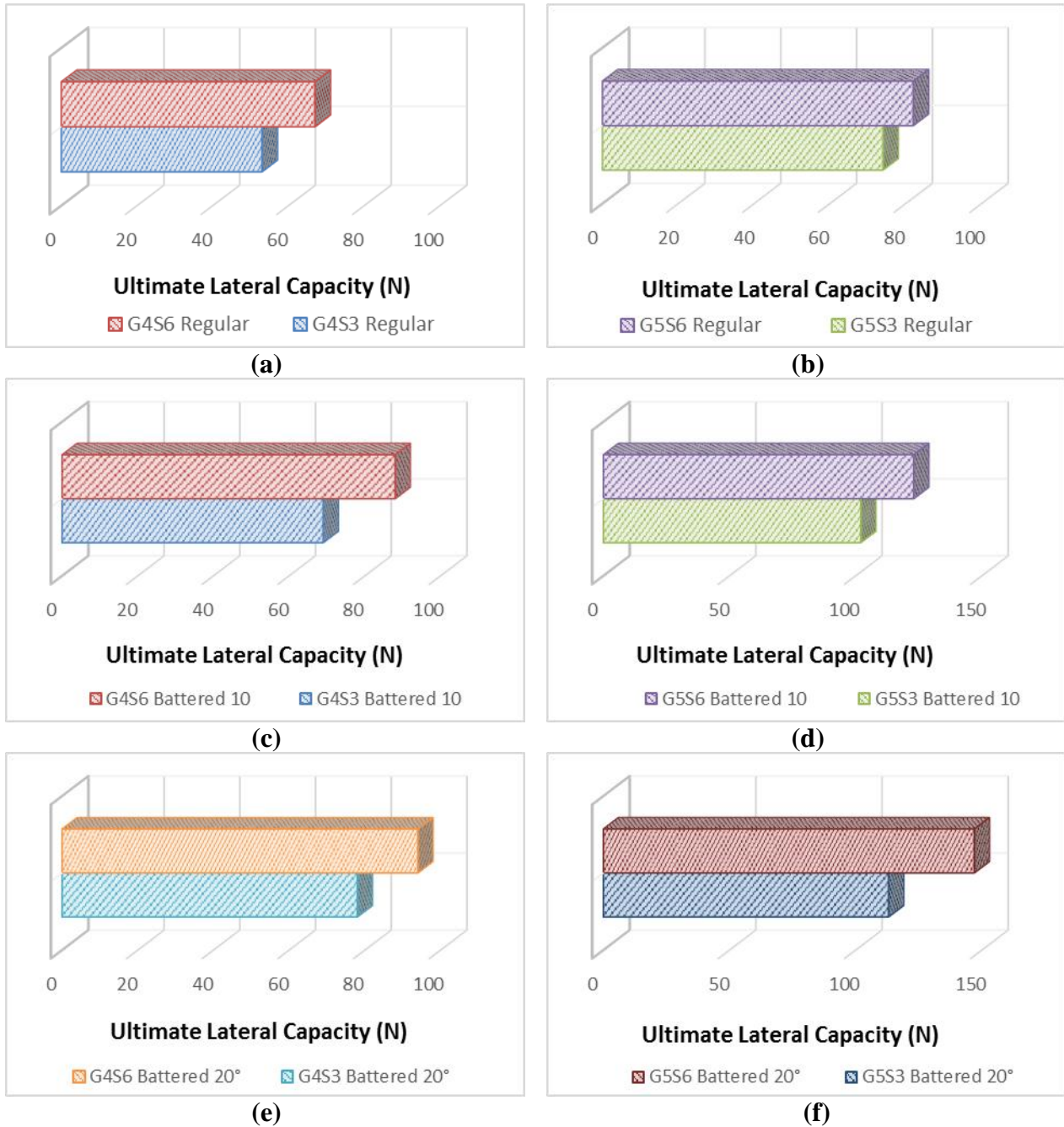
(d)



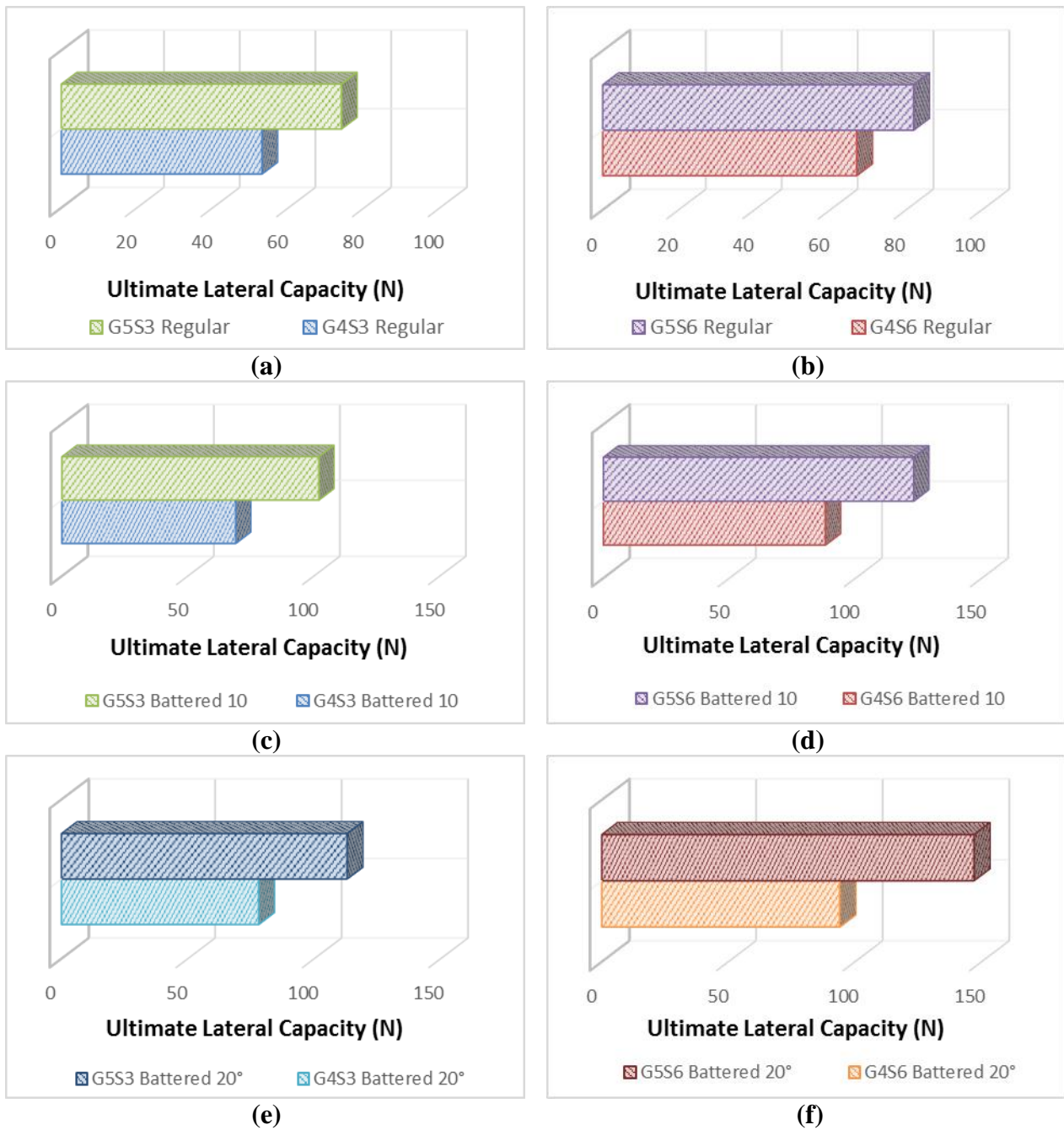
(e)

Figure 2. Continued.





**Figure 3.** Effect of (s/d) on ultimate lateral capacity for Battered and regular piles  
(a) G4 Pattern Regular (b) G5 Pattern Regular (c) G4 Pattern Battered 10° (d) G5 Pattern Battered 10° (e) G4 Pattern Battered 20° (f) G5 Pattern Battered 20°.



**Figure 4.** Effect of Group configuration on ultimate lateral capacity for Battered and regular piles (a) G4 and G5 Pattern, (s/d) =3 Regular (b) G4 and G5 Pattern, (s/d) =6 Regular (c) G4 and G5 Pattern, (s/d) =3 Battered 10° (d) G4 and G5 Pattern, (s/d) =6 Battered 10° (e) G4 and G5 Pattern, (s/d) =3 Battered 20° (e) G4 and G5 Pattern, (s/d) =6 Battered 20°.