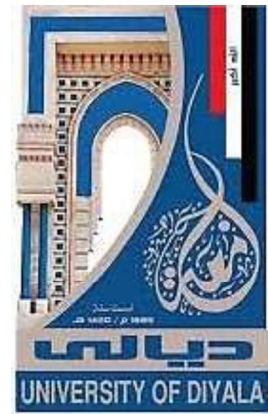


**Ministry of Higher Education  
and Scientific Research  
University of Diyala  
College of Engineering**



# **EXPERIMENTAL STUDY FOR LATERAL CYCLIC RESPONSE OF PILED-RAFT FOUNDATION IN MULTI-LAYER SOIL**

**A Thesis Submitted to the Council of the College of  
Engineering / University of Diyala in Partial  
Fulfillment of the Requirements for the Degree of  
Master of Science in Civil Engineering**

**BY**

**Wafaa Ali Saleh**

**(B.Sc. Civil Engineering, 1999)**

**Supervised by**

**Ph. D. Jasim M. Abbas**

**JULY 2020**

**IRAQ**

**Dhu Al-Hijjah 1441**

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

وَمَا تَوْفِيقِي إِلَّا بِاللَّهِ عَلَيْهِ تَوَكَّلْتُ  
وَالَيْهِ أُنِيبُ

صدق الله العظيم

سورة هود (٨٨)

# **CERTIFICATION OF THE SUPERVISOR**

I certify this thesis entitled “**Experimental Study for Lateral Cyclic Response of Piled-Raft Foundation in Multi-Layer Soil**” was prepared by “**Wafaa Ali Saleh**” was made my supervision in the University of Diyala in partial fulfillment of the requirements for the degree of master of science in civil engineering.

**Signature:**

**Name: Prof. Dr. Jasim M. Abbas**

**(Supervisor)**

**Date:    /    / 2020**

# COMMITTEE DECISION

We certify that we have read the thesis entitled (**Experimental Study for Lateral Cyclic Response of Piled-Raft Foundation in Multi-Layer Soil**). We have examined the student (**Wafaa Ali Saleh**) in its content and what is related with it, and in our opinion, it is adequate as a thesis for the degree of Master of Science in Civil Engineering.

## Examination Committee

## Signature

- 1-Prof. Dr. Jasim M. Abbas (Supervisor) .....
- 2-Assist. Prof. Dr. Qasim A. Aljanabi (Member) .....
- 3-Assist. Prof. Dr. Hassan O. Abbas (Member) .....
- 4-Prof. Dr. Qassun S. Mohammed Shafiqu (Chairman) .....

Prof. Dr. Khattab S. Abdul Al-Razzaq (Head of Department).....

The thesis was ratified at the Council of College of Engineering/  
University of Diyala.

**Signature**.....

**Name: Prof. Dr. Anees A.Khadom**

**Dean of College Engineering / University of Diyala**

**Date:**

## **SCIENTIFIC AMENDMENT**

I certify this thesis entitled “**Experimental Study for Lateral Cyclic Response of Piled-Raft Foundation in Multi-Layer Soil**” presented by “**Wafaa Ali Saleh**” has been evaluated scientifically; therefore, it is suitable for debate by examining committee.

**Signature:-**

**Name: Assist. Prof. Dr. Mohammed K. Fagher Al-Deen**

**Title: Assistant Professor**

**Address: College of Engineering/ University of Al-Kufa**

**Date:**

# LINGUISTIC AMENDMENT

I certify this thesis entitled “**Experimental Study for Lateral Cyclic Response of Piled-Raft Foundation in Multi-Layer Soil**” presented by “**Wafaa Ali Saleh**” has been corrected linguistically; therefore, it is suitable for debate by examining committee.

**Signature:-**

**Name: Assist. Dr. Amjad L. Jabbar**

**Title: Assistant**

**Address: University of Diyala / College of Education for  
Humanities**

**Date:**

# *Dedication*

*To.....*

*My father, who was the cause of my success*

*My mother, the sight of my eyes.*

*My husband, who supported me.*

*My brothers and my sons whose love flow in my veins.*

*Our honorable teachers who taught and rewarded us their knowledge.*

*Everyone, who wishes me success in my life,*

*I dedicate this humble work.*

*WAFAA ALI*

## ***ACKNOWLEDGEMENTS***

*Thanks are to Allah for all things which led me into the light during the critical time.*

*I would especially like to express my deep appreciation and sincere gratitude to my supervisor, Prof. Dr. Jasim M. Abbas for his supervision and his valuable guidance and assistance throughout conducting this work.*

*Appreciation and thanks to the Dean and the staff of the College of Engineering, University of Diyala and also the staff of Soil Laboratory and Road laboratory.*

*Very special thanks to Dr. Qutaiba G. Majeed and Lec. Yassir Nashaat for their kindest help and thanks to all my colleagues, for their help.*

*WAFAA ALI*



## **ABSTRACT**

### **Experimental Study for Lateral Cyclic Response of Piled-Raft Foundation in Multi-Layer Soil**

**By**

**Wafaa Ali Saleh**

**Supervised by:**

**Prof. Dr. Jasim M. Abbas**

## **ABSTRACT**

In piled raft foundation, the load-sharing system between the raft and piles are occurring to transfer the load coming from the superstructure to the soil. This foundation is usually supporting bridge piers, offshore platforms, marine structures and others that are required to resist not only static loading, but also lateral cyclic loading that developed from different sources of loadings such as wind and seismic loads. Therefore, this complex system in layered soil with different load combination needs more laboratory and numerical studies to improve the knowledge regarding the performance of such a problem.

This study offers an experimental study which is carried out to investigate the behaviour of laterally loaded pile raft models with three configurations ( $1 \times 2$ ,  $2 \times 1$ , and  $2 \times 2$ ) where slenderness ratio is 40. Furthermore, three layers soil are used with different percentage of saturation. In addition, many other parameters are selected; such as spacing between piles  $3D$ ,  $5D$ , and  $7D$  ( $D$  is a diameter of pile) and cross-sectional shape of the pile (i.e. square and circle). To simulate the loading to be as much close as possible to the real cases, different loading conditions are used such as number of cycles, level of the cyclic load ratio (CLR) and influence of axial load.

The results of the study indicated that deflection and bending moment profiles behaviour increase with an increasing number of cycles for all spacing of piled raft foundation models. Correspondingly, in case of pure lateral cyclic load (without vertical loads) where spacing to diameter ratio is 3, the results illustrated that at the critical cyclic load level  $CLR=60\%$  for 100 cycles, the lateral deflection is about 42%, 31%, and 44% more than at  $CLR=40\%$  of piled raft models (1×2), (2×1) and (2×2) respectively.

Furthermore, it found that the presence of vertical loads has reduced the lateral displacement and bending moment profiles in all cases. For circular pile shape group, the reduction in lateral displacement at 100 cycles was approximately 19%, 14% and 44% for models 1×2, 2×1 and 2×2 respectively, whereas for square shape, the percentage of the reduction were about 26%, 36%, and 34% respectively. The results also indicated that the increase in the lateral resistance in the group of square piles compared to a circular pile under pure lateral loading conditions within the group 1 × 2, 2 × 1 and 2 × 2 were about 16%, 20% and 23% respectively.

The results demonstrated that lateral deflection and bending moment values of this model in saturated clay soil were less than in partially saturated clay soil and closer to the dry soil of about (35% and 13%) respectively.

Finally, this study illustrated that maximum bending moment for trailing row was less than the leading row for circular piled raft models 1×2, 2×1, and 2×2 by about 16%, 17%, and 7% respectively, whereas the results for square model were about 22%, 13%, and 9% respectively.

## TABLE OF CONTENTS

Item	Heading	Page
<b>ABSTRACT</b>		VII
<b>CONTENTS</b>		IX
<b>LIST OF FIGURES</b>		XII
<b>LIST OF PLATES</b>		XV
<b>LIST OF TABLES</b>		XVI
<b>LIST OF SYMBOLS</b>		XVII
<b>LIST OF ABBREVIATIONS</b>		XIX
<b>CHAPTER ONE</b>	<b>INTRODUCTION</b>	
1.1	Introduction	1
1.2	Statement of the problem	3
1.3	Objectives of the Study	4
1.4	Thesis Outline	5
<b>CHAPTER TWO</b>	<b>REVIEW OF LITERATURE</b>	
2.1	Introduction	6
2.2	Cyclic Loading	7
2.3	Design Criteria for Laterally Loaded Piles	8
2.4	Pile- Soil Response to Lateral Loads	9
2.5	Unsaturated Soil	10
2.6	Unsaturated Soil Phases	12
2.6.1	The Contractile Skin (Surface Tension)	12
2.6.2	Concept of the Suction	12
2.6.3	Capillarity	13
2.7	Ultimate Lateral Resistance of a Single Pile	14
2.8	Ultimate Lateral Resistance of Pile Group	17
2.9	The Ultimate Capacity of Piled Raft	20
2.10	Interactions in Piled Raft Foundation	21
2.11	Previous Experimental Studies	23

2.12	Summary	26
<b>CHAPTER THREE</b>	<b>APPARATUS, MATERIALS, AND TESTING TECHNIQUES</b>	
3.1	Introduction	27
3.2	Model of Piled Raft System	27
3.2.1	Model of Pile	27
3.2.2	Pile Cap	29
3.3	Soil Properties	32
3.4	Setting Up of Geotechnical Model	36
3.4.1	Steel Soil Tank	36
3.4.2	Steel Loading Frame	37
3.4.3	Lateral Static Loading Device	38
3.4.4	Lateral Cyclic Loading Device	39
3.4.4.1	Motor-Gear System	40
3.4.4.2	Controlling Electronic Circuit Unit	41
3.4.5	Linear Variation Displacement Transducer (LVDTs)	42
3.4.6	Load Cell	43
3.5	Strain Gauge	44
3.5.1	The Strain Gauges Installation	46
3.5.2	The strain measuring (Strain Indicator)	46
3.5.3	Calibration of Data Acquisition System (Strain Indicator)	47
3.6	Calibrated electrical resistance gauge	48
3.7	Sand Raining Technique	49
3.8	Soil Deposit Preparation	51
3.8.1	Sand Deposit Preparation	52
3.8.2	Clay Deposit Preparation	52
3.9	Testing Procedure	53
3.10	Providing Two-Way Lateral Cyclic Loading	55
3.11	Testing Program	56

<b>CHAPTER FOUR</b>	<b>PRESENTATION AND ANALYSIS OF RESULTS</b>	
4.1	Introduction	58
4.2	Parametric of Study	58
4.3	Failure Criteria under the Effect of Static Load	59
4.4	Results of Static Loading Test for Piled Raft System	60
4.4.1	Estimate of Ultimate Axial Load Capacity	60
4.4.2	Estimate of Ultimate Lateral Load Capacity	64
4.5	Piled Raft foundation under Vertical and Lateral Cyclic Loading	67
4.5.1	Lateral Load-Deflection Response of the Piled Raft	68
4.5.1.1	The Effect of Group Configuration and Pile Spacing on Load- Deflection Behaviour	68
4.5.1.2	Influence of Number of Cycles on Load- Deflection Behaviour	73
4.5.1.3	Effect of Cyclic Load Ratio(CLR) on Deflection of Piled Raft Head	78
4.5.1.4	Effect of Degree of Saturation on load-deflection Curves	82
4.5.1.5	The Effect of Cross-Section Pile Shape on Lateral Response of Piled Raft	85
4.5.2	Response of Vertical Load – Displacement in Piled Raft	89
4.5.3	Distribution of the bending moment along the pile	96
<b>CHAPTER FIVE</b>	<b>CONCLUSIONS AND RECOMMENDATIONS</b>	
5.1	General	111
5.2	Conclusions	111
5.3	Recommendations for Future Research	113
	<b>REFERENCES</b>	114
	Appendix A	A-1
	Appendix B	B-1

## LIST OF FIGURES

NO.	Title	Page
2.1	Cyclic loading types (Peng et al., 2011)	8
2.2	Pile-soil response to lateral load and moment (Budhu, 2002)	10
2.3	Generalized world of soil mechanics(Fredlund, 1996)	11
2.4	Mechanical equilibrium for capillary rise in small-diameter tube	14
2.5	Failure Modes of Vertical Piles under Lateral Loads (Broms, 1964b)	15
2.6	Ultimate Lateral Resistance of Short Piles in Granular Soils(Broms 1964a)	16
2.7	Ultimate Lateral Resistance of Long Piles in Granular Soils (Broms,1964a)	16
2.8	Failure Mechanisms of Pile Groups (Fleming, 1992)	18
2.9	A gap formation around the pile group during cyclic loading in clay soil (Basack and Bhattacharya 2009)	19
2.10	Asemi-ellipsoid formed around the pile in sandy soil (Basack and Bhattacharya, 2009)	20
2.11	Different possible failure mechanisms of piled raft (Franke et al., 2000)	21
2.12	Raft and plied-raft foundation (Maharaj, 2003)	21
2.13	The interactions in a piled raft foundation system (El-Mossallamy and Franke, 1997)	22
3.1	Stress-strain curve for aluminum pipes	29
3.2	Arrangement of piles in a group a) (2×1) b) (1×2) c) (2×2)	32
3.3	Sand Grain Size Distribution Curve	33
3.4	Soil Strength Parameters Based on the Direct Shear Test	33
3.5	Compaction Curve for Clay Soil	35
3.6	Sketch showing lateral loading apparatus	39
3.7	Sketch indicating the location of strain gauges along the pile.	45
3.8	Sketch indicating calibration of strain indicator	47
3.9	Calibration of sand density	50
3.10	Schematic showing the system with multi-layered soil	52
3.11	Two-Way lateral cyclic loading shape	55
3.12	Flow chart for testing program	57
4.1	Axial load-Settlement relationship for piled raft models (1×2) and (2×1) (a) Circular pile (b) Square pile	63

4.2	Axial load-Settlement relationship for piled raft model (2×2) (a) Circular pile (b) Square pile	63
4.3	Load-Deflection curve for piled raft model (1×2) (a) Circular pile (b) Square pile	65
4.4	Load-Deflection curve for piled raft model (2×1) (a) Circular pile (b) Square pile	66
4.5	Load-Deflection curve for piled raft model (2×2) (a) Circular pile (b) Square pile	66
4.6	Load-Deflection Behaviour of Piled Raft Model (1×2) at 100 cycles under pure lateral and combined loads, (a) Circular pile, (b) Square pile	69
4.7	Load-Deflection Behaviour of Piled Raft Model (2×1) at 100 cycles under pure lateral and combined loads, (a) Circular pile, (b) Square pile	70
4.8	Load-Deflection Behaviour of Piled Raft Model (2×2) at 100 cycles under pure lateral and combined loads, (a) Circular pile, (b) Square pile	71
4.9	Effect of number of cycles on the load-deflection curve of piled raft model (1×2) with (S/D=3) under pure lateral and combined loading conditions (a)circular pile – (b) square pile	75
4.10	Effect of number of cycles on the load-deflection curve of piled raft model (2×1) with (S/D=3) under pure lateral and combined loading conditions (a)circular pile – (b) square pile	76
4.11	Effect of number of cycles on the load-deflection curve of piled raft model (2×2) with (S/D=3) under pure lateral and combined loading conditions (a)circular pile – (b) square pile	77
4.12	Effect of cyclic load ratio(CLR) on a lateral deflection of a circular piled raft model (1×2) under (a)pure lateral loading (b) combined loading	79
4.13	Effect of cyclic load ratio(CLR) on a lateral deflection of a circular piled raft model (2×1) under (a)pure lateral loading (b) combined loading	80
4.14	Effect of cyclic load ratio(CLR) on a lateral deflection of a circular piled raft model (2×2) under (a)pure lateral loading (b) combined loading	81
4.15	Effect of degree of saturation on a lateral deflection of a circular piled raft model (2×2) embedded in multi-layered soil (a) dry clay soil– (b) partially saturated clay soil - (c) saturated clay soil.	84
4.16	Comparison of lateral deflection of (i.e.Square and Circular) pile in a group model (1×2) (a)pure lateral loading (b) combined loading	86
4.17	Comparison of lateral deflection of (i.e.Square and Circular) pile in a group model (2×1) (a)pure lateral loading (b) combined loading	87
4.18	Comparison of lateral deflection of (i.e.Square and Circular) pile in a group model (2×2) (a)pure lateral loading (b) combined loading	88

4.19	Upward vertical displacement versus the number of cycles of piled raft model (1×2) with (S/D=3) under pure lateral loading (V= 0%Qall). (a) Circular pile, (b) Square pile	91
4.20	Upward vertical displacement versus the number of cycles of piled raft model (2×1) with (S/D=3) under pure lateral loading (V= 0%Qall). (a) Circular pile, (b) Square pile	92
4.21	Upward vertical displacement versus the number of cycles of piled raft model (2×2) with (S/D=3) under pure lateral loading (V= 0%Qall). (a) Circular pile, (b) Square pile	92
4.22	Upward vertical displacement versus spacing between piles under pure lateral loading (V= 0%Qall) at 100 cycles of piled raft models (a) (1×2), (b) (2×1), (c) (2×2)	93
4.23	Downward displacement versus spacing between piles under combined loading (V= 100%Qall) at 100 cycles of circular piled raft model (2×2) with changing degree of saturation (a)Dry clay (b)Partially saturated clay (c) Saturated clay	94
4.24	Downward displacement versus spacing between piles under combined loading (V=100%Qall) at 100 cycles of piled raft models (a) (1×2), (b) (2×1), (c) (2×2)	95
4.25	Distribution of the bending moment versus depth for a leading row of piled raft model (1×2) under pure lateral loading (V=0%Qall) at CLR=80%(170N) (a)Circular shape (b) Square shape	101
4.26	Distribution of the bending moment versus depth for a leading row of piled raft model (1×2) under combined loading (V=100%Qall) at CLR=80% (a)Circular shape (b) Square shape	102
4.27	Distribution of the bending moment versus depth for a leading row of piled raft model (2×1) under pure lateral loading (V=0%Qall) at CLR=80% (170N) (a)Circular shape (b) Square shape	103
4.28	Distribution of the bending moment versus depth for a leading row of piled raft model (2×1) under combined loading (V=100%Qall) at CLR=80% (a)Circular shape (b) Square shape	104
4.29	Distribution of the bending moment versus depth for a leading row of piled raft model (2×2) under pure lateral loading (V=0%Qall) at CLR=80% (170N) (a)Circular shape (b) Square shape	105
4.30	Distribution of the bending moment versus depth for a leading row of piled raft model (2×2) under combined loading (V=100%Qall) at CLR=80% (a)Circular shape (b) Square shape	106
4.31	Distribution of the bending moment versus depth for a leading row of circular piled raft model (2×2) under pure lateral loading (V=0%Qall) at CLR=80% (a)Dry clay (b) partially saturated clay (c) Saturated clay	107
4.32	Distribution of the bending moment versus depth for a leading row of circular piled raft model (2×2) under combined loading (V=100%Qall) at CLR=80% (a)Dry clay (b) partially saturated clay(c) Saturated clay	108
4.33	Effect location of piles in a row on bending moment profile under pure lateral load (V=0%Qall) at CLR=80% after 100 cycles of circular and square piled raft model (a) 1×2 (b) 2×1 (c) 2×2	109
4.34	Effect location of piles in a row on bending moment profile under combined load (V=100%Qall) at CLR=80% after 100 cycles of circular and square piled raft model (a) 1×2 (b) 2×1 (c) 2×2	110



## LIST OF PLATES

NO.	Title	Page
1.1	Failure of pile foundation due to lateral loads	4
3.1	Tensile test of aluminum pipes	28
3.2	Parts of pile's cap	30
3.3	Loading frame for the testing device	37
3.4	Static loading device during the test.	38
3.5	Cyclic loading apparatus	40
3.6	Motor-Gear system	41
3.7	Control circuit components	42
3.8	Linear Variation Displacement Transducer (LVDTs)	43
3.9	Load cell	43
3.10	Electrical Strain gauge, SB tape and compatible adhesive type (CN).	45
3.11	Strain Gauges installing: (a) Applying CN-E Adhesive (b) Installing the strain gauge (c) Covering with SB tape	46
3.12	Strain Indicator	47
3.13	Data Logger model EM50 and Matric Potential sensor	48
3.14	Cans setting for individual density	50
3.15	Raining technique	51
3.16	Placing the soil pressure gauge at a specified depth	53
3.17	Compacting clay soil	54
3.18	Piles installation using hand auger	54
4.1	deformation around the piles (a) at the beginning of the test (b)at CLR=0.6	82

## LIST OF TABLES

<b>NO.</b>	<b>Title</b>	<b>Page</b>
3.1	Mechanical properties of aluminum piles used in group	29
3.2	Summarize the physical properties of the sandy soil	34
3.3	Clay Soil Properties	35
3.4	Strain gauge specifications	44
4.1	Summary of the ultimate and allowable vertical load of piled raft models (2×1) and (1×2) L/D=40	64
4.2	Summary of the ultimate and allowable vertical load of piled raft models (2×2) L/D=40	64
4.3	Summary of the ultimate lateral loading results of piled raft models (1×2), (2×1) and (2×2)	67
4.4	Effect of pile spacing on lateral resistance of the cross-sectional shape of the pile	72
4.5	Effect of pile spacing on bending moment profile at CLR=80% of piled raft models (1×2), (2×1), and (2×2)	100

## LIST OF SYMBOLS

Symbol	Term
<i>c</i>	Cohesion
<i>C<sub>u</sub></i>	Coefficient of uniformity
<i>C<sub>c</sub></i>	Coefficient of Curvature
<i>D</i>	Pile diameter
<i>D<sub>50</sub></i>	Mean size of soil particles
<i>D<sub>10</sub></i>	Effective size at 10% passing
<i>D<sub>30</sub></i>	Grain size at 30% passing
<i>D<sub>60</sub></i>	Grain size at 60% passing
<i>D<sub>r</sub></i>	Relative density of soil
<i>E<sub>s</sub></i>	Soil Modulus
<i>EI</i>	Stiffness of pile section
<i>E</i>	Modulus of elasticity
<i>e</i>	Eccentricity of load
<i>e<sub>max</sub></i>	Maximum void ratio of soil
<i>e<sub>min</sub></i>	Minimum void ratio of soil
<i>f</i>	Frequency
<i>G<sub>s</sub></i>	Specific gravity
<i>H</i>	Lateral load applied on the pile head
<i>HZ</i>	Hertz
<i>I</i>	Moment of inertia
<i>L</i>	Embedded length of pile
<i>L/D</i>	Slenderness ratio of pile
<i>M</i>	Bending moment
<i>p</i>	The soil pressure per unit length of the pile
<i>V</i>	Vertical load
<i>Q<sub>all.</sub></i>	Allowable vertical load
<i>Q<sub>ult.</sub></i>	Ultimate vertical load
<i>r</i>	Outside radius of the pipe

$y$	Pile deflection
$\gamma$	Unit weight of soil
$\gamma_d$	Initial dry unit weight of soil
$\varepsilon$	Measured strain
$\phi$	Angle of internal friction
$Q_b$	End bearing (base) resistance of pile
$Q_s$	Skin friction (shaft) resistance of pile
$q_b$	Ultimate bearing capacity at pile base
$q_s$	Ultimate skin friction of pile shaft
$A_b$	Area of pile base
$A_s$	Perimeter area of the pile shaft
$q'$	Effective vertical stress at pile base
$N_q$	Bearing capacity factor for pile foundation
$\sigma_{av}$	Average vertical effective stress in a given layer
$K$	Lateral earth pressure coefficient
$\delta$	Angle of soil-pile friction (in degree)
$R$	Radius of curvature of the meniscus
$T_c$	Surface tension of water
$U_w$	Pore water pressure
$U_a$	Air pressure

## LIST OF ABBREVIATION

<b>Abbreviation</b>	<b>Term</b>
<b>USCS</b>	Unified Soil Classification System
<b>API</b>	American Petroleum Institute
<b>ASTM</b>	American Society For Testing and Materials
<b>CLR</b>	Ratio of magnitude of cyclic lateral load to static ultimate lateral capacity of the pile
<b>LVDT</b>	Linear Variation Displacement Transducer
<b>SSI</b>	Soil-structure interaction
<b>PLC</b>	Programmable Logic Controller

# ***CHAPTER ONE***

## ***INTRODUCTION***

# CHAPTER ONE

## INTRODUCTION

### **1.1 Introduction**

Day after day, the demand for ample infrastructure increases due to the growing population. To accommodate this increasing, it is required to construct high-rise buildings, express highways, and bridges, etc. Making these skyscrapers require stable and economical foundations to be built because very high self-weight, wind loads and seismic loads come through the structure and subsequently increasing load on the foundation. Many traditional foundations are available, for example shallow foundation, raft foundation, and pile, but using one of these foundations is not suitable and economical for such high-rise buildings that have a tremendous load to be carried by the substructure. In such condition, the pile-raft foundation can be considered the best solution for these structures (Kumar and Kumar, 2018).

In general, raft is designed as rigid for resisting high moment and differential settlement, which is a result of the intensity of load and relative stiffness of raft and soil. In the case of conventional foundation design, it must be ensured that the building load will be supported by either the raft or the piles with sufficient safety to avoid failure of the load-bearing capacity and loss of overall stability. In piled raft foundation, the contributions of the raft, as well as piles, are taken into account to check the ultimate load-bearing capacity and the suitability for use of the overall system (Singh and Singh, 2011a).

Piled raft foundation consists of three load-bearing elements: piles, raft and subsoil. According to their stiffness, the raft distributes the total load transferred from the structure as contact pressure below the raft and load over each of the piles. In piled raft foundation, the contributions of the raft and piles are taken into consideration to verify the ultimate bearing capacity and the serviceability of the overall system (Singh and Singh, 2011b). The principal benefit of using piled raft foundation is a reduction in the total number of piles due to perhaps only 60-75% of the total structural load carried by the piles and a portion of the load is carried by the raft (Randolph, 1994)

Piled raft foundations are among the most commonly used support structures for offshore projects (Ghalesari et al., 2015), which are often subjected to significant cyclic lateral loads caused by wave actions. Cyclic lateral loads that effected on pile structures can be caused by wind, waves, earth pressure, and water pressure. Furthermore, construction processes and mechanical compaction cyclically load the soil.

The behaviour of a vertical pile that is subjected to repetitive lateral loads affected by several variables such as geometrical and structural properties of the pile, characteristics of the lateral load (e.g. rate of cyclic load ratio), the properties of soil in which the pile is embedded and the change in soil properties as the pile is loaded repetitively (Long and Vanneste, 1994).

The rate of lateral loads in the site of onshore structures is approximately 10-20% of the axial load whereas for offshore structures this rate can reach at about 30% (Rao et al., 1998). Therefore, the amount of horizontal displacement generated by lateral force over the allowable can cause damage to engineering structure (Bartlett and Youd, 1995). Therefore, it is important to consider a lateral force when designing structures that are subject to cyclic loading to meet safety requirements.



## **1.2 Statement of the Problem**

Designing deep foundations to withstand seismic loading is a reality. Seismic loading of structures and foundations reaches its most critical state as a cyclic lateral force. The response of soils and foundations to repetitive lateral forces is highly complex, relegating most design methods to be based upon overly conservative rules-of-thumb (Moss et al., 1998). Plate (1.1) show the failure of pile foundation due to lateral loads by action of several resources.

Unsaturated soil is the most common material encountered in the field of geotechnical engineering. Yet, mechanics of partially saturated soil lags far behind that of saturated soil. A partially saturated soil is a complex multi-phase system consisting of air, water and solid material whose response is a function of the stress state, moisture condition and other internal variables present within the soil. The difficulties of the experimental and theoretical operations delayed the development of understanding the behaviour of partially saturated soils.

Depending on the soil conditions and intensity of loading, piled raft foundations are the most prevalent kind of deep foundations used to support high rise building which are often designed to resist the dead load with adequate safety factor during their life. However, piled raft foundations are subjected to significant axial and lateral cyclic loads, these are generated by several sources. This is particularly true for the piled raft system of offshore structures, which are subjected to rocking motions caused by wave actions, as well as onshore structures, which in turn, makes the structure in danger.

The studies examining the effect of cyclic loading on the piled raft foundation in multi-layered with partially saturated soil are limited and there is need for improvement and an increasing number of researchers begins the working on improving and understanding the mechanical behaviour of such complex system. The work that is presented in this thesis will help to understand

the effects of various parameters on the overall performance of the piled-raft foundation through experimental work using small models tested under two-way cyclic lateral loading.



*Plate (1.1): Failure of pile foundation due to lateral loads*

### **1.3 Objectives of the Study**

Cyclic lateral loading is one aspect of the problem that offshore foundations and other applications have encountered and adds to the complexity of these structures (Brown et al., 1988).

The main work focused on several points:

1. Identifying of the response of piled rafts embedded in multi-layered soil and their variation of properties with changing the degree of saturation for clay layer under two-way cyclic loading.
2. Investigation of the influence of the axial load, number of cycles as well as cyclic load ratio (CLR) on the lateral resistance of the pile-raft system under

pure lateral and combined loading conditions by evaluating the variation of the lateral displacement and the bending moment along the pile shaft.

3. Assessing the effect of cross-sectional shape and spacing between the piles in the group on the response of piled raft models under pure lateral and combined cyclic loading conditions.
4. Evaluating the best pattern under pure lateral and combined loading conditions which meets increased lateral resistance.

### **1.4 Thesis Outline**

The skeleton of the present thesis is divided into five chapters:

***Chapter One:*** gives a brief description of the piled raft problem under cyclic loading and describes the objectives of the study.

***Chapter Two:*** presents a brief review of previous experimental researches as well as field investigations on pile raft foundations to investigate the vertical and cyclic lateral loading of such foundations.

***Chapter Three:*** is devoted to offering the experimental setup used for modeling the piled raft system under cyclic loading in the laboratory, the properties of the soils used in this work, and their classification, besides the testing techniques and program.

***Chapter Four:*** presents the results of the study. Load-displacement curves represent the behaviour of different configurations of piled raft models and their lateral resistance.

***Chapter Five:*** summarizes the most important conclusions of experimental research as well as recommendations for future work.