

**EXPERIMENTAL AND NUMERICAL STUDIES ON
PILE BEHAVIOR UNDER COMBINED
LATERAL AND UPLIFT LOADS**

K. MADHUSUDAN REDDY



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
NEW DELHI-110016, INDIA**

MARCH 2015

**EXPERIMENTAL AND NUMERICAL STUDIES ON
PILE BEHAVIOR UNDER COMBINED
LATERAL AND UPLIFT LOADS**

by

K. MADHUSUDAN REDDY

Department of Civil Engineering

Submitted

in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MARCH 2015

Dedicated to My Beloved Father
Late Shri. K. Chandra Reddy
and
My Family

CERTIFICATE

This is to certify that the thesis entitled "**EXPERIMENTAL AND NUMERICAL STUDIES ON PILE BEHAVIOR UNDER COMBINED LATERAL AND UPLIFT LOADS**" submitted by **Mr. K. Madhusudan Reddy** to the Indian Institute of Technology Delhi, is a record of the bonafide research work carried out by him under my supervision and guidance. This thesis work, in my opinion, has reached the standard, fulfilling the requirements for **Doctor of Philosophy** degree. The research report and the results presented in this thesis have not been submitted, in part or full, to any other university or institute, for the award of any degree or diploma.

(Dr. R. Ayothiraman)

Associate Professor

Department of Civil Engineering

Indian Institute of Technology Delhi

New Delhi-110016

INDIA

ACKNOWLEDGEMENTS

Completion of this doctoral dissertation was possible with the support of several people. I would like to express my sincere gratitude to all of them. First of all, I am deeply indebted to my adviser, **Dr. R. Ayothiraman**, Associate Professor, Department of Civil Engineering, for his fundamental role in my doctoral work. I am extremely grateful to my research guide, for his valuable guidance, scholarly inputs and consistent encouragement; I have been receiving throughout this research work. This feat was possible only because of the unconditional support provided by Sir. A person with an amicable and positive disposition, Sir has always made himself available to in every aspect of work, despite his busy schedules and I consider it as a great opportunity to do my doctoral programme under his guidance and to learn from his research expertise. Thank you Sir, for all your help and support.

The author expresses his gratitude to SRC: **Prof. A. K. Jain (Chairman)**, **Prof. G.V Ramana (Member)** and **Prof. Santosh Kapuria (Member)** for their valuable input at different stages of this thesis work, for improving the quality of the work. In addition to his critical comments on the work as a SRC member, **Prof. G.V. Ramana**, has been providing his constant moral support as well to carry out the research work. I am very grateful to him.

I am also thankful to **Prof. Manoj Datta**, Head of Civil Engineering Department, **Prof. A.K. Nagpal**, **Prof. A.K. Gosain** and **Prof. A.K. Jain**, former Heads of Civil Engineering Department and **Laboratory In-charge(s)**, Geotechnical Engineering Lab, for providing necessary space, fund, equipments etc. for conducting this research work.

I also would like sincerely thank the faculty members of Geotechnical Engineering Section: **Prof. K.G. Sharma**, **Prof. K.S. Rao**, **Prof. J.T. Shahu**, **Dr. B. Manna** and **Dr. Tanusree Chakraborty** for providing encouragement and suggestions.

This thesis would not have come to a successful completion, without the help I received from **Ms. G. Shilpa**. She provided me technical inputs for FE modelling and worked with me in FE analysis. Special note of recognition, appreciation goes to her.

I am deeply indebted to **Prof. K. Rajagopal, Department of Civil Engineering, IIT Madras**, for permitting me to work in PLAXIS 3D at IIT Madras. My stay over at IIT Madras and interaction with him has helped me a lot to complete the FE modelling.

Few faculty members of the Civil Engineering Department, especially **Dr. Vasant Matsagar and Dr. K.R.C. Rao**, have been very kind enough to extend their help at various phases of my work, whenever I approached them, and I do hereby acknowledge all of them.

I extend my thanks to all geotechnical lab staff: **Mr. Manoj Kumar Neelam, Mr. D.S. Gusain, Mr. D. Biswas and Mr. Munni Lal** for their kind help and support during the experimental work. And I also acknowledge the help from **Mr. Amit Bundela**, and **Mr. N.R. Gehlot**, for their hold up for the computational lab facilities.

I take this opportunity to thank my friends **Sumanth, Chandrakanth, Pradeep, Praveen, Satish, Kanaujia, Mohan Rao Sir and Prasad sir** for their emotional support during the tough period of my research work. Special thanks to **Raghav and Aditya** for spending their valuable time in compiling the thesis.

I must thank **Dinesh and Kailash** for their hard work in preparation of soil bed for conducting the model experiments,.

I owe a lot to my parents, who encouraged and helped me at every stage of my personal and academic life, and longed to see this achievement come true. I deeply miss my father, **Chandra Reddy**, who is not with me to share this joy. The Author wishes to thank his family for their understanding and support. My wife **Sneha**, who has been with me all these years and has made them the best years of my life. I thank my daughter, **Shraddha** has been a source of patience, encouragement and love.

Above all, I owe it all to Almighty God for granting me the wisdom, health and strength to undertake this research task and enabling me to its completion.

Date: 23.02.2015

K. Madhusudan Reddy

ABSTRACT

Pile foundations are generally used to support vertical compressive loads from superstructures, but may also be subjected to lateral, uplift and moment loading in a few structures such as transmission towers, mooring systems for ocean surface or submerged platforms, tall chimneys, jetty structures, etc. Under these circumstances, the pile would resultantly be subjected to combined loading and moments. Hence, an understanding of pile behavior under the combined loads/moments is very important for design. The present study primarily aims at investigating the pile behavior under combined lateral and uplift loads.

1-*g* model experiments were conducted in the laboratory for studying pile behavior under combined lateral and uplift loading. Model aluminium single pile of different *L/D* ratios: 18, 28 and 38 were used. Sand having varying density conditions: loose-medium dense, dense and very dense ($RD = 40\%$, 70% and 90%) were simulated. Model piles were subjected to both independent lateral/uplift load and combined load tests. Combined loading tests were done in two series: (i) lateral pile load tests with constant uplift load to investigate the effect of constant uplift load on pile behavior under lateral load and (ii) uplift load tests with constant lateral load to investigate the effect of constant lateral load on pile behavior under uplift load.

The ultimate pile capacity under lateral and uplift modes under combined loading were interpreted from the load-deflection/displacement curves measured from experiments. It was found that the ultimate pile capacity in both lateral and uplift modes was significantly affected by the combined loading. The pile head displacement/deflection during the combined loading was also measured and analyzed. It was seen that the displacement/deflection had increased substantially

under combined loading compared to independent loading, which indicates that the displacement/deflection which are considered to be within the limits under independent loading, may exceed the limits under combined loading. This indicates that the effect of combined loading needs to be properly accounted for in the practical design. Combined load capacity factor for both lateral and uplift modes are defined and presented in this study.

The finite element modeling of the soil-pile system subjected to combined loading was also carried out using PLAXIS 3D software. The pile was idealized as a linear elastic material. The soil was modeled using hardening soil model. 16-noded interface elements were used between soil and pile to simulate the pile-soil interface characteristics with a strength reduction factor of 0.7. Initial stress conditions were simulated by considering K_0 -procedure. The standard fixities were applied to the boundaries. Validation of FE model was done using the load test data reported in literature for independent lateral and uplift loading. The data of model experiments conducted at $RD = 70\%$ were considered to compare the predicted pile behavior under combined loading by FE modeling. The results predicted by the FE analysis were compared with the experimentally measured pile behavior under combined loading and it was found that the FE model was able to predict the pile behavior under combined lateral and uplift loading with good accuracy. The limitations of model experiments are also highlighted and suggestions for future research are given.

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS	iii
ABSTRACT	v
TABLE OF CONTENTS	vii
LIST OF FIGURES	xiii
LIST OF TABLES	xix
NOTATIONS	xxi
CHAPTER 1 RELEVANCE OF RESEARCH	1
1.1 GENERAL	1
1.2 PILE BEHAVIOR UNDER INDEPENDENT LOADING	3
1.2.1 Compressive Loading	3
1.2.2 Lateral Loading	4
1.2.3 Uplift Loading	6
1.3 PILE BEHAVIOR UNDER COMBINED LOADING	7
1.3.1 Pile Behavior under Compressive and Lateral Loading	7
1.3.2 Pile Behavior under Compressive and Uplift Loading	8
1.3.3 Pile Behavior under Lateral and Uplift Loading	9
1.4 OBJECTIVES	10
1.5 SCOPE	11

1.6	OUTLINE OF THE THESIS	11
CHAPTER 2	REVIEW OF LITERATURE	13
2.1	INTRODUCTION	13
2.2	PILE BEHAVIOR UNDER COMPRESSIVE LOAD	13
2.3	PILE BEHAVIOR UNDER LATERAL LOAD	25
2.4	PILE BEHAVIOR UNDER UPLIFT LOAD	31
2.5	PILE BEHAVIOR UNDER COMBINED LOADING	42
2.5.1	Combined Lateral and Compressive Loading	42
2.5.2	Combined Uplift and Compressive Loading	48
2.5.3	Combined Lateral and Uplift Loading	50
2.6	CRITICAL ASSESSMENT OF LITERATURE	53
2.7	SUMMARY	54
CHAPTER 3	EXPERIMENTAL INVESTIGATION	55
3.1	INTRODUCTION	55
3.2	MATERIAL USED	55
3.2.1	Soil: Sand	55
3.2.2	Model Pile	61
3.3	EXPERIMENTAL SETUP	66
3.3.1	Test Tank Dimensions	66
3.3.2	Test Setup and Loading Arrangement	66

3.4	SAND BED PREPARATION AND PILE INSTALLATION	70
3.4.1	Sand Bed Preparation for 40 % Relative Density	70
3.4.2	Sand Bed Preparation for 70 % and 90 % Relative Density	73
3.4.3	Pile Installation	76
3.5	TEST PROCEDURE	76
3.5.1	Independent Load Tests	76
3.5.2	Combined Load Tests	77
3.6	TEST PROGRAM	78
3.7	SUMMARY	78
CHAPTER 4	ANALYSIS AND DISCUSSION OF EXPERIMENTAL RESULTS	81
4.1	INTRODUCTION	81
4.2	PILE BEHAVIOR UNDER INDEPENDENT LOADING	81
4.2.1	Pile Behavior under Independent Lateral Load	81
4.2.2	Pile Behavior under Independent Uplift Load	85
4.3	PILE BEHAVIOR UNDER COMBINED LOADING	90
4.3.1	Effect of Uplift Load on Pile Behavior under Lateral Load	90
4.3.2	Effect of Lateral Load on Pile Behavior under Uplift Load	107

4.4	COMBINED LOAD CAPACITY FACTOR	126
4.4.1	Combined Lateral Capacity Factor	126
4.4.2	Combined Uplift Capacity Factor	128
4.5	SUMMARY	131
CHAPTER 5	FINITE ELEMENT ANALYSIS	133
5.1	GENERAL	133
5.2	MODELING OF SOIL-PILE INTERACTION IN PLAXIS 3D	133
5.2.1	Modeling of Pile	133
5.2.2	Modeling of Soil	134
5.2.3	Modeling of Soil-Pile Interface	137
5.2.4	Size of Model and Boundary Conditions	139
5.2.5	Analysis/Calculation Stages	140
5.3	VALIDATION PROBLEMS	140
5.3.1	Pile Behavior under Independent Lateral Loading	140
5.3.2	Pile Behavior under Uplift Loading	145
5.4	MODELING OF PILE BEHAVIOR UNDER COMBINED LOADING	149
5.4.1	Problem Statement	149
5.4.2	Details of Modeling	149

5.5	RESULTS AND DISCUSSION	151
5.5.1	Effect of Constant Uplift Load on Laterally Loaded Pile	151
5.5.2	Effect of Constant Lateral Load on Pile Response under Uplift Loading	159
5.6	SUMMARY	168
CHAPTER 6	SUMMARY AND CONCLUSIONS	169
6.1	SUMMARY	169
6.2	CONCLUSIONS	170
6.3	SUGGESTIONS FOR FUTURE RESEARCH	173
	REFERENCES	175
	LIST OF PUBLICATIONS BASED ON THIS THESIS	193
	BRIEF BIO DATA OF K. MADHUSUDAN REDDY	195