OPTIMIZATION OF UPLIFT CAPACITY OF TRANSMISSION TOWER FOUNDATIONS

Udagedara Pushpika Pradeep Gunasena

(138811E)

Dissertation submitted in partial fulfillment of the requirements for the degree Master of Engineering

Department of Civil Engineering

University of Moratuwa

Sri Lanka

May 2017

DECLARATION OF THE CANDIDATE AND SUPERVISORS

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

U.G.P.P. Gunasena

24th May, 2017

The above candidate has carried out research for the Masters dissertation under my supervision.

Prof. H.S. Thilakasiri

24th May, 2017

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to my supervisors Prof. H.S. Thilakasiri and Dr. L.I.N. De Silva for the continuous support given for the research, for their patience, motivation, enthusiasm, and immense knowledge. Their guidance helped me in all the time of research and writing of this dissertation.

My sincere thanks go to Eng. Mr. N.T. Colombage; former Deputy General Manager in Ceylon Electricity Board, for giving me support and encourage me for doing this thesis.

Further, I must thank all the lecturers engaged in the MEng course sessions for making our vision broader, providing us with the opportunity to improve our knowledge in various fields.

It is a great pleasure to remember the kind cooperation of all my colleagues who have helped me in this Post Graduate programme by extending their support during the research period.

My special thanks go to my wife, Vindya and my parents Mr. and Mrs. Gunasena, for supporting and tolerating my engagement on this work.

U.G.P.P. Gunasena

ABSTRACT

Transmission tower lines using lattice towers and concrete foundations are the common practice in most of the countries all over the world. A significant amount of the cost of the transmission tower line is spent for the tower foundation construction.

Uplift capacity of transmission tower foundation is determined based on the assumption that, the uplift force is resisted by the weight of the footing and the weight of the soil inside the volume of inverted frustum. Hence, the uplift capacity of the foundation is a major aspect of determining the dimensions of the tower foundation. However, the values of the frustum angle seem to be arbitrary and the failure pattern is more likely to be varied from the assumed pattern. Apart from that, the frustum angle is unsymmetrical for the inclined loadings. Further, the estimated uplift capacity shall also be reassessed according to the failure plane variations.

As the first step of this study, a research survey was conducted on the available empirical methods of estimating the uplift capacity. Data were collected on transmission tower types and their foundation types based on different soil categories.

This report will use PLAXIS; a finite element software to analyze the uplift capacity of transmission tower foundation. A comparison between the results from the software analysis and the capacities given by empirical methods is included in the report. An evaluation on the assumptions made on frustum angle, composition of uplift capacity to determine the uplift capacity of the transmission tower foundations is also given in the report. This analysis also includes the failure patterns, uplift capacity, composition variation of uplift capacity for different types of foundations used for transmission towers. Conclusively, this will evaluate and make a recommendation on determination the uplift capacity of transmission tower foundation, assumption of the frustum angle and the composition of the uplift capacity.

CONTENTS

Page

Declaration of the candidate and supervisors ……... ii

Acknowledgement …… iii

Abstract …… iv

Contents ..…….. v

List of figures ……...viii

List of tables …… xi

List of abbreviations …… xii

List of appendices ….……xiii

Chapter 1…….…….. 01

Introduction

1.1 Background/Survey of previous work…… 01

1.1.1 Dead loads on tower structure……...03

1.1.2 Imposed loads on tower structure…… 03

1.1.3 Wind loads…… 04

1.2 Objectives …… 07

1.3 Methodology... ……08

Chapter 2 …….. 11

Literature Review

2.1 Current uplift capacity calculation method……...11

2.2 Uplift calculation methods in literature…… 11

2.2.1 Cone method …… 11

2.2.1.1 Dewberry method…….. 11

2.2.1.2 Balla's method……... 12

2.2.1.3 Matsuo and Tagawa method……..13

2.2.1.4 Mariupol'skii method…….14

2.2.1.5 Mayerhof and Adams method……15

2.2.2 Earth pressure method……...16

2.2.2.1 Mueller method……..16

2.2.2.2 Mors method…….. 17
2.2.2.3 Motorcolombus method……. 18
2.2.3 Semi-empirical methods…….....…….. 18
2.2.3.1 Bankers and Kondners method…….. 19
2.2.3.2 Turners method…….. 19
2.2.3.3 Biarez and Barraud method……... 20
2.3 PLAXIS software....…… ……22
2.3.1 Soil element models……..22
2.3.1.1 Linear-elastic model…….……..22
2.3.1.2 Mohr-coulomb model…….…….. 22
2.3.1.3 Soft soil model…….…….. 22
2.3.1.4 Hardening soil model..…….…….. 22
2.3.1.5 Soft soil creep model..…….…….. 23
2.3.2 Calculation procedure…….…….. 23
2.3.2.1 Calculation steps….…….…….. 23
2.3.2.2 Tolerated error……...…….…….. 24
2.3.2.3 Arc-length control…...…….…….. 24
2.3.3 Validation of PLAXIS model for the analysis…..…….....25
2.4 Soil parameters for the defined soil types for tower foundations……. 25

Chapter 3……27
Analysis of foundations for uplift for different soil types
3.1 PLAXIS model validation…….27
3.2 Correlation between uplift capacity and different soil and foundation parameters for undercut foundations……..…….. 28
3.2.1 Development of PLAXIS model for the analysis……...28
3.2.2 Uplift capacity variation of the undercut foundation with the width of the foundation…….……29
3.2.3 Uplift capacity variation of the undercut foundation with the friction angle of soil…… ……... …….…….. 31
3.2.4 Uplift capacity variation of the undercut foundation with the unit weight of soil…..……... 33

3.2.5 Uplift capacity variation of the undercut foundation with the cohesion of soil……..…….....35
3.2.6 Uplift capacity variation of the undercut foundation with the elastic modulus of soil…….....36
3.2.7 Uplift capacity variation of the undercut foundation with the stub direction and the direction of load application...…….....37
3.2.8 Composition of uplift capacity for variation of soil properties and Dimension of undercut foundation..…….....38
3.3 Correlations between uplift capacity and different soil and foundation parameters for foundations without undercut ……38
3.3.1 Uplift capacity variation of without undercut foundations with the width of the foundation…….…… 38
3.3.2 Uplift capacity variation of without undercut foundations with the friction angle of soil……... …….…….. 42
3.3.3 Uplift capacity variation of without undercut foundations with the unit weight of soil ……...…...43
3.3.4 Uplift capacity variation of without undercut foundations with the cohesion of soil…….....44
3.3.5 Uplift capacity variation of without undercut foundations with the direction of load application and stub angle…….....45
3.3.6 Composition of uplift capacity for variation of soil properties and dimension of foundations without undercut……...46
3.4 Analysis of TD1-S2 soil type foundations using PLAXIS 3D and empirical formulas…… 47
3.4.1 PLAXIS 3D analysis of TD1-S2 foundation……..47
3.4.2 Uplift capacity calculation of TD1-S2 foundation using empirical formulas 50
3.4.3 PLAXIS 3D analysis of TD1 – S3, S4 and S5 foundations and comparison of results with empirical calculations 51
3.4.4 Analysis of S2 soil type foundations 54

Chapter 4 ……57

Discussion

4.1 Appropriateness of assumed failure planes in empirical methods for the purpose of calculation of uplift capacity of towers ……..……57

4.2 Suitability of proposed empirical equations use for the calculation of uplift capacity of tower foundations…… 60

4.3 Composition of uplift capacity of foundation……...61

Chapter 5 ……...64

Conclusions

5.1 Conclusions ……...64

5.2 Suggestions to be implemented…… 65

References ...……..66

Appendices ……68

List of Figures

		Page
Figure 1.1	Basic anatomy of transmission towers	02
Figure 1.2	Wind span and weight span of the tower at center	03
Figure 1.3	Assumed soil behavior when foundation subject to uplift	07
Figure 2.1	Assumed failure plane in Dewberry method	12
Figure 2.2	Assumed failure plane for Balla method	12
Figure 2.3	Configuration of Matsuo and Tagawa method	14
Figure 2.4	Failure pattern of Mariupol'skii method	14
Figure 2.5	Assumed failure plane in Earth pressure method	16
Figure 2.6	Configuration of method proposed by Mueller	17
Figure 2.7	Proposed stress distribution by Mors	17
Figure 2.8	Different soil condition defined for Biarez and Barraud method	20
Figure 2.9	Numerical solution vs exact solution	24
Figure 2.10	Iterative procedure for (a) normal load control (b) Arc-length control	25
Figure 3.1	Physical model used to determine the failure mechanism and Uplift capacity of shallow foundation	27
Figure 3.2	PLAXIS model developed to analyse the uplift capacity of foundation with vertical uplift load	29
Figure 3.3	Uplift capacities given by different methods for the variation of the width of undercut foundations	31
Figure 3.4	Uplift capacities given by different methods for the variation of friction angle of soil	33
Figure 3.5	Uplift capacities given by different methods for the variation of unit weight of soil	35

Figure 3.6	Uplift capacities given by different methods for the variation of cohesion of soil	37
Figure 3.7	Uplift capacities given by different method for the variation of the width of foundation without undercut	41
Figure 3.8	Failure patterns of (a) undercut foundation (b) foundation without undercut	41
Figure 3.9	Uplift capacities given by different method for the variation of the friction angle of soil for foundation without undercut	42
Figure 3.10	Uplift capacities given by different method for the variation of the unit weight of soil for foundation without undercut	44
Figure 3.11	Uplift capacities given by different method for the variation of the cohesion of soil for foundation without undercut	45
Figure 3.12	TD1-S2 type tower foundation	47
Figure 3.13	PLAXIS 3D model of TD1-S2 foundation	47
Figure 3.14	Total displacement curve of TD1-S2 tower foundation	48
Figure 3.15	Incremental strain of TD1-S2 foundation	48
Figure 3.16	Measured angles of assumed failure plane from the PLAXIS Analysis	49
Figure 3.17	Composition of uplift capacity of TD1-S2 tower foundation	50
Figure 3.18	Failure patterns of TD1 foundations for the soil categories S2, S3 S4 and S5	51
Figure 3.19	Composition of uplift capacities of TD1 tower foundation types	52
Figure 3.20	Uplift capacity of TD1 foundations derived from PLAXIS analysis and empirical formulas	53
Figure 3.21	Failure patterns of S2 type soil for TD1, TD3 and TD6 towers	54
Figure 3.22	Composition of uplift capacity of S2 foundations	55

Figure 3.23 Uplift capacities of S2 foundations derived from different methods 56
Figure 4.1 Observations of 5m width undercut foundation (a) total displacements (b) incremental strains 58
Figure 4.2 (a) Displacement curve for PLAXIS 3D (b) Assumed failure plane in Mariupol'skii method 59
Figure 4.3 Analysis results for 5m width foundation (a) Failure plane from incremental strain curve (b) Total displacement curve 59
Figure 4.4 Incremental strains of 5m undercut foundation (a) vertical uplift force (b) 15 degree angle uplift force 63

List of Tables

		Page
Table 1.1	Tower types used in transmission lines	04
Table 1.2	Soil types categorized for the tower foundation design	06
Table 2.1	Selected soil type from soil categories to model the transmission tower foundation	25
Table 2.2	Soil parameters for selected soil types for the use of PLAXIS model	26
Table 3.1	Comparison of results by Physical and PLAXIS model	28
Table 3.2	Calculated uplift capacities for the variation of foundation width using PLAXIS 3D analysis and empirical methods	30
Table 3.3	Calculated uplift capacities of undercut foundation for the variation of soil friction angle using PLAXIS 3D analysis and empirical methods	32
Table 3.4	Calculated uplift capacities for the variation of unit weight of soil using PLAXIS 3D analysis and empirical methods for undercut foundations	34
Table 3.5	Calculated uplift capacities for the variation of cohesion of soil using PLAXIS 3D analysis and empirical methods for undercut foundations	36
Table 3.6	Calculated uplift capacities for the variation of direction of uplift Force applied, using PLAXIS 3D for 3m and 5m undercut Foundations	38
Table 3.7	Composition of the analysed uplift capacities of undercut foundation using PLAXIS 3D for different parameter variations	39
Table 3.8	Calculated uplift capacities for the variation of foundation width using PLAXIS 3D and empirical methods for foundations	

	without undercut	40
Table 3.9	Calculated uplift capacities for the variation of friction angle of soil using PLAXIS 3D and empirical methods for foundations without undercut	42
Table 3.10	Calculated uplift capacities for the variation of unit weight of soil using PLAXIS 3D and empirical methods for foundations without undercut	43
Table 3.11	Calculated uplift capacities for the variation of cohesion of soil using PLAXIS 3D and empirical methods for foundations without undercut	44
Table 3.12	Calculated uplift capacities for the variation of direction of uplift force applied, using PLAXIS 3D for 5m foundations without undercut	45
Table 3.13	Composition of the analysed uplift capacities of foundation without undercut using PLAXIS 3D for different parameter variations	46
Table 3.14	Uplift capacity calculated using empirical formula for TD1-S2 foundation	50
Table 3.15	Breakdown of uplift capacities of TD1 tower foundation types Using PLAXIS 3D analysis	52
Table 3.16	Uplift capacity of foundations of TD1 tower types	53
Table 3.17	Uplift capacities of S2 foundations for all tower types	55

LIST OF ABBREVIATIONS

CEB	Ceylon Electricity Board
PLS-CADD	Power Line Systems – Computer Aided Design and Drafting
SAP	Structural Analysis Program
PLAXIS	Plasticity Axi-Symmetry
3D	Three dimensional
FEM	Finite element model

LIST OF APPENDICES

Appendix 1: Type drawings of analyzed tower foundations

Appendix 2: Value of K_d for Dewberry method

Appendix 3: Graphs to determine Balla's coefficients B_1 and B_2

Appendix 4: Pullout strength factors K_1, K_2, K_3 AND K_4 for Matsuo and Tagawa method

Appendix 5: Dimensionless function μ for Mariupol'skii method

Appendix 6: Shape factor coefficient and uplift coefficient for Mayerhof and Adams method

Appendix 7: Factors $M_{c0}, M_{\varphi 0}$ and $M_{\gamma 0}$ for Biarez and Barraud method