



E46979



**PHYSICAL AND ANALYTICAL MODELING OF GEOSYNTHETIC
REINFORCED PILE SUPPORTED EMBANKMENTS**

MR. UTHANA CHAIYAPORN

**A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF ENGINEERING (CIVIL ENGINEERING)
FACULTY OF ENGINEERING
KING MONGKUT'S UNIVERSITY OF TECHNOLOGY THONBURI
2010**

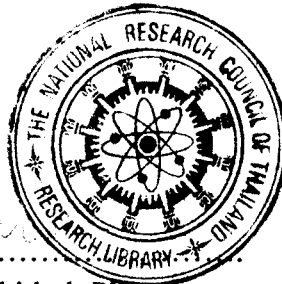


Physical and Analytical Modeling of Geosynthetic Reinforced Pile Supported Embankments

Mr. Uthana Chaiyaporn B.Eng. (Civil Engineering)

A Thesis Submitted in Partial Fulfillment
of the Requirements for
the Degree of Master of Engineering (Civil Engineering)
Faculty of Engineering
King Mongkut's University of Technology Thonburi
2010

Thesis Committee



Warat Kongkitkul
.....
(Asst. Prof. Warat Kongkitkul, Ph.D.)

Chairman of Thesis Committee

Sompote Youwai
.....
(Asst. Prof. Sompote Youwai, D.Eng.)

Member and Thesis Advisor

Pornkasem Jongpradist
.....
(Asst. Prof. Pornkasem Jongpradist, Ph.D.)

Member and Thesis Co-Advisor

B. Vardhanabuti
.....
(Lect. Barames Vardhanabuti, Ph.D.)

Member

Copyright reserved

Thesis Title	Physical and Analytical Modeling of Geosynthetic - Reinforced Pile - Supported Embankments
Thesis Credits	12
Candidate	Mr. Uthana Chaiyaporn
Thesis Advisors	Asst. Prof. Dr. Sompote Youwai Asst. Prof. Dr. Pornkasem Jongpradist
Program	Master of Engineering
Field of Study	Civil Engineering (Geotechnical Engineering)
Department	Civil Engineering
Faculty	Engineering
B.E.	2553

E46979

Abstract

This research is aimed to study the behaviors of geosynthetic - reinforced pile - supported embankments (GRPS) by physical model tests and develop an analytical equation to predict its behaviors. From test results, the uniformly distributed external load slightly affected the vertical stress of soil between piles when arching mechanism was fully developed. The induced stress on pile top of the reinforced case was higher than that of the unreinforced case and slightly increased with increase of stiffness of geosynthetic. The analytical method was verified with several current design methods and experimental results. The developed method showed reasonable agreement with experimental results. The failure envelop of arching effect was postulated to be a pyramid shape with a slope $\beta \approx 70^\circ$. The progress analytical equations which include the effect of soil below the reinforcement reasonably predicted the tensile force of geosynthetics in physical model tests.

Keywords: Soil Arching / Geosynthetic / Piled Supported Embankments

หัวข้อวิทยานิพนธ์	แบบจำลองในห้องปฏิบัติการและแบบจำลองทางคณิตศาสตร์ของการเสริมกำลังคันทางที่รองรับด้วยเสาเข็มโดยใช้แผ่นใยสังเคราะห์
หน่วยกิต	12
ผู้เขียน	นายยุทธนา ไชยพร
อาจารย์ที่ปรึกษา	ผศ.ดร. สมโพธิ อยู่ไว ผศ.ดร. พรเกษม จงประดิษฐ์
หลักสูตร	วิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชา	วิศวกรรมโยธา (วิศวกรรมเทคนิคธรณี)
ภาควิชา	วิศวกรรมโยธา
คณะ	วิศวกรรมศาสตร์
พ.ศ.	2553

E46979

บทคัดย่อ

จุดมุ่งหมายของงานวิจัยนี้เป็นการศึกษาถึงพฤติกรรมของการปรับปรุงคุณภาพดินโดยใช้แผ่นใยสังเคราะห์รองรับด้วยเสาเข็ม (GRPS) โดยแบบจำลองในห้องปฏิบัติการ และพัฒนาสมการในการทำนายพฤติกรรมต่างๆ ที่เกิดขึ้นของระบบ จากผลการทดสอบในห้องปฏิบัติการพบว่าหน่วยแรงภายนอกมีผลเพียงเล็กน้อยต่อหน่วยแรงที่เกิดขึ้นต่อคันที่อยู่ระหว่างเสาเข็ม นอกจากนี้ยังพบว่าเมื่อการพัฒนาส่วนโค้งของการกระจายหน่วยแรงเกิดขึ้นเต็มที่หน่วยแรงที่เกิดขึ้นที่ส่วนบนสุดของเสาเข็มในกรณีที่มีการเสริมแผ่นใยสังเคราะห์จะมีความมากกว่ากรณีที่ไม่มีการเสริมแผ่นใยสังเคราะห์ หน่วยแรงที่เกิดขึ้นที่หัวเสาเข็มจะแปรผันกับการเพิ่มความแข็งแรงของแผ่นใยสังเคราะห์ งานวิจัยนี้ยังได้ปรับปรุงแบบจำลองทางคณิตศาสตร์เพื่อจำลองพฤติกรรมของแบบจำลองในห้องปฏิบัติการและทำการเปรียบเทียบกับวิธีการวิเคราะห์แบบอื่นๆ จากการจำลองพฤติกรรมของแบบจำลองในห้องปฏิบัติการพบว่าสมการที่ได้รับการปรับปรุงมีความสอดคล้องกับผลการทดสอบในห้องปฏิบัติการ มุมของการกระจายหน่วยแรงจะจำลองให้อยู่ในรูปของพีรามิดที่มีมุมกับแนวราบประมาณ 70 องศา สมการที่ได้รับการปรับปรุงนี้ได้เพิ่มอิทธิพลของหน่วยแรงด้านจากชั้นดินที่รองรับแผ่นใยสังเคราะห์ หน่วยแรงดึงที่เกิดขึ้นในแผ่นใยสังเคราะห์ที่ได้จากสมการที่ปรับปรุงแล้วมีความสอดคล้องอย่างดีกับผลการทดสอบแบบจำลองในห้องปฏิบัติการ

คำสำคัญ : ส่วนโค้งของการกระจายหน่วยแรง / แผ่นใยสังเคราะห์ / เสาเข็มรองรับคันดิน

ACKNOWLEDGEMENTS

The author would like to express his gratitude to his advisor and co-advisor, Asst. Prof. Dr. Sompote Youwai and Asst. Prof. Dr. Pornkasem Jongpradist for excellent guidance and strong support throughout his study. Without their help in both academic and personal concerns, this thesis work could not have been completed. Sincere appreciation is also extended to the other members of the committees, Asst. Prof. Dr. Warat Kongkitkul and Dr. Barames Vardhanabhuti for this help, encouragement, suggestions, constructive comments and serving as members of his thesis examination committees. In addition, the author is also grateful to the Tencate Geosynthetics (Thailand) Ltd. for providing the geogrid which used in this study and the financial supports from the KMUTT research fund.

Thanks are also extended to his friends in Geotechnical Engineering Division for their help to conduct laboratory test, especially Mr. Bordin Tangcharoensuk, Mr. Watthano Tabsombut, Mr. Thitikorn Posribink, Mr. Nuttapong Fudsiri, Mr. Komsan Thaisri, Ms. Thitapan Chantachot, and Mr. Jukkavut Tansakul.

Finally, the author would like to thank his father, mother and a sister for their constant supports and encouragements during his study at the King Mongkut's University of Technology Thonburi.

CONTENTS

	PAGE
ENGLISH ABSTRACT	ii
THAI ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
CONTENTS	v
LIST OF TABLES	vii
LIST OF FIGURES	ix
LIST OF SYMBOLS	xii
CHAPTER	
1. INTRODUCTION	1
1.1 General	1
1.2 State of Study	1
1.3 Objectives of the Study	2
1.4 Scope and Limitation of the Study	2
2. LITERATURE REVIEW	3
2.1 Introduction	3
2.2 Theory of Soil Arching	3
2.2.1 Load Transfer Mechanism	5
2.3 Current Design Procedures for Piled Embankment	6
2.3.1 British Standard BS8006	6
2.3.1.1 Embankment and load transfer	7
2.3.1.2 Geotextile tensile load	8
2.4 Other methods	10
2.4.1 Hewlett and Randolph (1988) method	10
2.4.2 Russell and Pierpoint (1997) method	11
2.4.3 The Swedish method	12
2.4.4 Terzaghi (1943) method	13
2.4.5 Guido (1987) method	13
2.5 Case histories	14
2.6 Model studies	16
3. METHODOLOGY	19
3.1 Introduction	19
3.2 Model theory and basics of the own model tests	19
3.3 Test-materials	20
3.3.1 Bearing elements	20
3.3.2 Model sand	20
3.3.3 Geosynthetics reinforcement	22
3.3.4 Soft layer	23

3.4	Measuring procedures	24
3.4.1	General	25
3.4.2	Vertical force measurement	25
3.4.3	Strain in geosynthetics (Strain gauges)	26
3.5	Model test variations and extent	28
3.6	Model preparation and dimensions	29
3.6.1	Model building and external pressuring	29
3.6.2	Model dimensions	32
3.7	Analytical Solution	33
3.7.1	Analytical solution of a piled embankment without geosynthetics (Reference test)	34
3.7.2	Analytical solution of geosynthetic reinforced piled supported embankments	34
4.	TEST RESULTS AND DISCUSSIONS	35
4.1	Introduction	35
4.2	Test Results and Discussion	35
4.3	Analytical solution	40
4.3.1	Analytical solution of a piled embankment without geosynthetics (Reference test)	40
4.3.2	Analytical solution of geosynthetic reinforced piled supported embankments	42
4.4	Comparison with Current Design Methods	46
4.4.1	Homogeneous sand embankment without geogrid	46
4.4.2	Homogeneous sand embankment with geogrid (Tensile stiffness, $J = 250 \text{ kN/m}$)	49
4.4.3	Homogeneous sand embankment with geogrid (Tensile stiffness, $J = 125 \text{ kN/m}$)	56
5.	CONCLUSIONS	63
5.1	Conclusions	63
5.2	Recommendations for Further Studies	63
	REFERENCES	64
	APPENDIXS	
A	Calculation of vertical stress on pile cap, efficiency and tensile force in geogrid	69
B	Comparisons of vertical stress on pile cap, efficiency and tensile force in geogrid with existing methods	73
	CURRICULUM VITAE	83

LIST OF TABLES

TABLE		PAGE
2.1	Summary of partial factors used in the design of piled embankments (BS8006, 1995)	7
3.1	Dimensionless parameter	19
3.2	Geosynthetic reinforcements used in this study	23
3.3	Summary of the Geosynthetic Reinforced Pile Supported Embankments	29
4.1	Arching slope β back-calculated from the measured vertical stress on pile	40
B1	Comparison of the vertical stress on pile from the experimental with analytical method (50 cm embankment height)	75
B2	Comparison of the vertical stress on pile from the experimental with analytical method (30 cm embankment height)	75
B3	Comparison of the vertical stress on pile from the experimental with analytical method (Apply external pressure at 50 cm embankment height)	75
B4	Comparison of the vertical stress on pile from the experimental with analytical method (Apply external pressure at 30 cm embankment height)	75
B5	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (50 cm embankment height)	76
B6	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Pluviation stage of 50 cm embankment height)	76
B7	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Pluviation stage of 30 cm embankment height)	76
B8	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Pluviation stage of 30 cm embankment height)	76
B9	Comparison of the efficiency value with existing methods of reinforcement case, $J = 250 \text{ kN/m}$ (50 cm embankment height)	77
B10	Comparison of the efficiency value with existing methods of reinforcement case, $J = 250 \text{ kN/m}$ (30 cm embankment height)	77
B11	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	77
B12	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	77
B13	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	78
B14	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	78

B15	Comparison of the efficiency value with existing methods of reinforcement case, $J = 250 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	78
B16	Comparison of the efficiency value with existing methods of reinforcement case, $J = 250 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	78
B17	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (50 cm embankment height)	79
B18	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Pluviation stage of 50 cm embankment height)	79
B19	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Pluviation stage of 30 cm embankment height)	79
B20	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Pluviation stage of 30 cm embankment height)	79
B21	Comparison of the efficiency value with existing methods of reinforcement case, $J = 125 \text{ kN/m}$ (50 cm embankment height)	80
B22	Comparison of the efficiency value with existing methods of reinforcement case, $J = 125 \text{ kN/m}$ (30 cm embankment height)	80
B23	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	80
B24	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	80
B25	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	81
B26	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	81
B27	Comparison of the efficiency value with existing methods of reinforcement case, $J = 125 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	81
B28	Comparison of the efficiency value with existing methods of reinforcement case, $J = 125 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	81
B29	Comparison of the efficiency value between reinforces and unreinforced with embankment height	82
B30	Comparison of the tensile force in geogrid value between tensile stiffness 125 and 250 kN/m	82

LIST OF FIGURES

FIGURE	PAGE
2.1 Load transfer mechanism of GRPS system	3
2.2 The soil mass overlying a potential void (McKelvey, 1994)	4
2.3 The formation of a true arch (Void under soil mass) (McKelvey, 1994)	4
2.4 Soil mass collapses to form an inverted arch (McKelvey, 1994)	4
2.5 Load Transfer Mechanisms (Li et al., 2002)	5
2.6 Piled embankment loads according to BS8006	8
2.7 Horizontal force at the side of embankment (after BS8006)	9
2.8 Hemispherical domes model (Hewlett & Randolph, 1988)	11
2.9 Study's geometry of Russell and Pierpoint (1997) method.	12
2.10 Study's geometry of Carsson (1987) method.	12
2.11 Study's geometry of Terzaghi (1943) method.	13
2.12 Study's geometry of Guido et al. (1987) method.	14
2.13 Study's geometry of Low et al. (1994)	17
3.1 Particle photo of KMUTT sand	20
3.2 Illustration of CDTC test performed on KMUTT sand at the Tokyo University of Science (TUS).	21
3.3 Typical pluviation manner in preparing triaxial sand specimen (after Miura and Toki, 1982).	22
3.4 Multiple sieving pluviation apparatus for preparing embankment layer	22
3.5 PET Miragrid GX80/30	23
3.6 Stress – strain behaviour of polyurethane foam	24
3.7 The position of the load cell to measure the vertical force in the pile element	25
3.8 Calibration result of load cell used in this study	26
3.9 The positions of the strain gauges on the reinforcement	26
3.10 The calibration factor of the strain gauges on the reinforcement ($J = 250 \text{ kN/m}$)	27
3.11 The calibration factor of the strain gauges on the reinforcement ($J = 125 \text{ kN/m}$)	28
3.12 Pluviation for preparing embankment layer	30
3.13 Tension force record	30
3.14 Vertical force on pile cap record	31
3.15 Pressuring scheme of model test	31
3.16 Steel plate and reaction frame of model test	32
3.17 Model dimensions of full arching case	32
3.18 Model dimensions of partial arching case	33
3.19 Model stand of full and partial arching case	33
3.20 Schematic geometry of analytical solution for reference case	34
3.21 represent the procedure of analytical solution for reinforced type	34
4.1 Comparison of the vertical stress on pile from experimental in the case of 50 cm embankment height	36
4.2 Comparison of the tensile force in geogrid from experimental in the case of 50 cm embankment height	36
4.3 Comparison of the vertical stress on pile from experimental in the case of	37

	30 cm embankment height	
4.4	Comparison of the tensile force in geogrid from experimental in the case of 30 cm embankment height	37
4.5	The vertical stress on pile from experimental in the case of 50 cm embankment height	38
4.6	The vertical stress on pile from experimental of 50 cm embankment height (Apply pressure stage)	38
4.7	The vertical stress on pile from experimental in the case of 30 cm embankment height	39
4.8	The vertical stress on pile from experimental of 30 cm embankment height (Apply pressure stage)	39
4.9	Pyramid geometry of analytical solution	41
4.10	Idealized of geosynthetics overlying pile caps and soft soil	42
4.11	The circular arc assumption (Fluet et al., 1986, Van Impe, 1989 and Low et al., 1994)	43
4.12	Idealized stress distribution on geosynthetics	44
4.13	Soil-geosynthetic interface shear stress	45
4.14	Comparison of the vertical stress on pile between experimental and analytical of 50 cm embankment height (Pluviation stage)	47
4.15	Comparison of the vertical stress on pile between experimental and analytical of 30 cm embankment height (Pluviation stage)	47
4.16	Comparison of the vertical stress on pile between experimental and analytical of 50 cm embankment height (Apply pressure stage)	48
4.17	Comparison of the vertical stress on pile between experimental and analytical of 30 cm embankment height (Apply pressure stage)	48
4.18	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Pluviation stage of 50 cm embankment height)	50
4.19	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Pluviation stage of 50 cm embankment height)	50
4.20	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	51
4.21	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Pluviation stage of 30 cm embankment height)	51
4.22	Comparison of the efficiency value with existing methods of reinforcement case, $J = 250 \text{ kN/m}$ (50 cm embankment height)	52
4.23	Comparison of the efficiency value with existing methods of reinforcement case, $J = 250 \text{ kN/m}$ (30 cm embankment height)	52
4.24	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	53
4.25	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	53

4.26	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	54
4.27	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 250 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	54
4.28	Comparison of the efficiency value with existing methods of reinforcement case, $J = 250 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	55
4.29	Comparison of the efficiency value with existing methods of reinforcement case, $J = 250 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	55
4.30	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (50 cm embankment height)	57
4.31	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Pluviation stage of 50 cm embankment height)	57
4.32	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Pluviation stage of 30 cm embankment height)	58
4.33	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Pluviation stage of 30 cm embankment height)	58
4.34	Comparison of the efficiency value with existing methods of reinforcement case, $J = 125 \text{ kN/m}$ (Pluviation stage of 50 cm embankment height)	59
4.35	Comparison of the efficiency value with existing methods of reinforcement case, $J = 125 \text{ kN/m}$ (Pluviation stage of 30 cm embankment height)	59
4.36	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	60
4.37	Comparison of the vertical stress on pile with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	60
4.38	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	61
4.39	Comparison of the tensile force in geogrid with existing methods of reinforcement case $J = 125 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	61
4.40	Comparison of the efficiency value with existing methods of reinforcement case, $J = 125 \text{ kN/m}$ (Apply pressure stage at 50 cm embankment height)	62
4.41	Comparison of the efficiency value with existing methods of reinforcement case, $J = 125 \text{ kN/m}$ (Apply pressure stage at 30 cm embankment height)	62
A1	Theoretical geosynthetic strain (Low, 1994)	72

LIST OF SYMBOLS

a	=	Pile cap width
C_c	=	Arching coefficient
c'	=	Effective cohesion of soil
c_u	=	Undrained shear strength of the soft foundation soil
D	=	Depth of soft foundation soil
D_r	=	Relative density
E	=	Efficiency
E_c	=	Elastic modulus of the soft ground
F_{piles}	=	The load supported by all the piles
F_{total}	=	The load corresponding to the overload and the weight of the embankment
f_q	=	Load factor of external live load
f_f	=	Load factor of external dead load
f_{fs}	=	Load factor of soil unit mass
f_{ms}	=	Soil material factors
f_p	=	Pull-out resistance of reinforcement
f_s	=	Sliding across surface of reinforcement
G_M	=	Stiffness of model
G_P	=	Stiffness of prototype
h	=	Height of the embankment
J	=	Tensile stiffness of geosynthetic
K_a	=	Active lateral earth pressure coefficient
K_p	=	Passive lateral earth pressure coefficient
L_M	=	Dimension of model
L_P	=	Dimension of prototype
q	=	Uniformly distributed external load
R	=	Radius of circular arc
S_{3D}	=	Stress reduction ratio
s	=	Center to center of pile spacing
s_L	=	Average vertical stress at the base of the embankment
T	=	Axial tension force of the geosynthetics
t	=	Maximum displacement midway between the pile cap
T_{rp}	=	Tensile load in the geosynthetic
T_{ds}	=	Tensile load in the geosynthetics for horizontal force of the embankment
W_l	=	Uniformly distributed line load
w_s	=	Surcharge intensity on top of the embankment
α	=	Ratio of maximum displacement midway between the pile caps to space of pile cap
β	=	Angle of arching

γ	=	Unit weight of soil
γ_{emb}	=	Unit weight of embankment
κ	=	Reduction factor for the length of surcharge load (on plane)
λ	=	Reduction factor
τ	=	Shear stress
ε_g	=	reinforcement strain
η_G	=	Scale factor for stiffness
η_L	=	Scale factor for dimension
ρ_{dmax}	=	maximum dry density
ϕ'_{cv}	=	Effective critical state friction angle
ϕ	=	Friction angle of sand
θ	=	Half angle of circular arc
σ'_c	=	Effective pressure acting on top of pile cap
σ_p	=	Average vertical stress acting on pile cap (with geosynthetic)
σ_{p0}	=	Average vertical stress acting on pile cap (without geosynthetic)
σ'_v	=	Average vertical stress at the base of the embankment
σ'_s	=	Vertical stress at the base of the embankment
σ_s	=	Average vertical stress acting on top of soft ground midway between pile caps (with geosynthetic)
σ_{s0}	=	Average vertical stress acting on top of soft ground midway between pile caps (without geosynthetic)