

**PERFORMANCE OF ON-GRADE SLABS ON EXPANSIVE SOILS
AT TABUK CITY – K.S.A.**

**BY
OSAMA MOSLEM MOHAMMED IBRAHIM**

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
In
Civil Engineering - Public Works

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2016

**PERFORMANCE OF ON-GRADE SLABS ON EXPANSIVE SOILS
AT TABUK CITY – K.S.A.**

**BY
OSAMA MOSLEM MOHAMMED IBRAHIM**

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
In
Civil Engineering - Public Works

Under the Supervision of
Prof. Dr. MOHAMED IBRAHIM AMER
Professor of Geotechnical Engineering
Faculty of Engineering – Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2016

PERFORMANCE OF ON-GRADE SLABS ON EXPANSIVE SOILS AT TABUK CITY – K.S.A.

BY

OSAMA MOSLEM MOHAMMED IBRAHIM

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

In
Civil Engineering - Public Works

Approved by the
Examining Committee

Prof. Dr. Mohamed Ibrahim Amer, Thesis Advisor
Professor of Geotechnical Engineering, Cairo University

Prof. Dr. Hussein Hamed El-Mamlouk, Internal Examiner
Professor of Geotechnical Engineering, Cairo University

Prof. Dr. Fathalla El-Nahhas, External Examiner
Professor of Geotechnical Engineering, Ain Shams University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT

2016

Name: Osama Moslem Mohamed Ibrahim
Date of Birth: 25/10/1980
Nationality: Egyptian
E-mail: O_moslem@yahoo.com
Phone: +21110827799
Address: 30 Mohamed Rashad - Al Nozha - Cairo
Registration Date: 15 July 2008
Degree: Doctor of Philosophy
Department: Civil Engineering - Public Works
Supervisor: Prof. Dr. Mohamed Ibrahim Amer
Examiners: Prof. Dr. Fathalla El-Nahhas (External examiner)
Prof Dr. Hussein Hamed El-Mamlouk (Internal Examiner)
Prof. Dr. Mohamed Ibrahim Amer (Thesis advisor)



Title of Thesis:

PERFORMANCE OF ON-GRADE SLABS ON EXPANSIVE SOILS AT TABUK
CITY – K.S.A.

Key Words:

Expansive soil, Swelling pressure, heave, granular anchor pile, slab.

Summary:

One of the techniques to reduce the heave problems is granular pile anchor foundation (GPAF). In this research, three slabs-on-grade are constructed at the field, the first slab as a regular slab-on-grade; the second was supported with granular pile anchor, while the third was supported on concrete pile anchor foundation (CPAF). The test area flooded by water for 64 days, the in situ swelling pressure measured as 49 KPa, Monitoring the performance of three slabs after wetting indicated that the CPAF and GPAF systems caused a 62% and 57% reduction in upward movement respectively. Furthermore, numerical models are analyzed, and a series of numerical models are constructed to study the effect of granular pile anchor in heave reduction at various lengths and diameters.

ACKNOWLEDGEMENT

The present work was completed under the supervision of **Prof. Dr. Mohamed Ibrahim Amer**, Professor of Geotechnical Engineering, Cairo University, and by great help from **Dr. Tamer Yahia El Kady**, Associate Professor of Geotechnical Engineering, Cairo University. I have the pleasure of working under their supervision. I express sincere appreciation for their helpful, generous advice and guidance throughout the period of this research.

Grateful acknowledgment is also made to Soil and Foundation Company (SAFCO) for their valuable helps during field work period.

Finally, I would like to express my deep feelings towards each member of my family to whom I owe every success in my life. My cordial thanks spread out to my wife for her support.

Table of Contents

Acknowledgments	i
Table of contents	ii
List of tables	v
List of figures	vi
List of abbreviations.....	ix
Abstract	x
CHAPTER 1: INTRODUCTION	1
CHAPTER 2: LITERATURE REVIEW	3
2.1 Background	3
2.2 Swelling process	5
2.3 Clay minerals	5
2.4 Swelling parameters	6
2.4.1 Swelling potential	6
2.4.2 Swelling pressure	6
2.5 Classification and identification of swelling soils	6
2.5.1 Classification methods	7
2.5.1.1 Atterberg limits	7
2.5.1.2 Clay content	11
2.5.2 Indirect methods for identifying swelling soils	13
2.5.2.1 Plasticity index	13
2.5.2.2 Clay activity	13
2.5.2.3 Clay fraction	16
2.5.2.4 Free swell test.....	17
2.5.2.5 Shrinkage index	18
2.5.2.6 Liquid limit	18
2.5.2.7 Soil expansion potential	18
2.5.2.8 Cation exchange capacity	19
2.5.2.9 Coefficient of Linear Extensibility	21
2.5.3 Direct methods for identifying swelling soils	22
2.5.3.1 Measurements of swell parameters by oedometer tests.....	22
2.5.3.2 Soil suction test	25
2.6 Heave prediction	26
2.6.1 Semi-empirical methods	26

2.6.1.1	Heave prediction using Texas method	26
2.6.1.2	Heave prediction using double oedometer test	27
2.6.1.3	Heave prediction using simplified oedometer test	27
2.6.1.4	Heave prediction using constant volume test	28
2.6.1.5	Heave prediction using stress change method	28
2.6.1.6	Heave prediction using suction change method	30
2.6.2	Empirical methods	31
2.7	Damage to expansive soil	35
2.8	Treatment methods of expansive soil	36
2.8.1	Foundation and structure design	36
2.8.1.1	Drilled pier and beam	38
2.8.1.2	Stiffened raft	39
2.8.1.3	Monolithic slab	41
2.8.1.4	Modified continuous perimeter footing	41
2.8.2	Sub-excavation and removal of expansive soil and replacement with non-expansive soil	42
2.8.2.1	Sand cushion method	42
2.8.2.2	Cohesive non swelling layer replacement	42
2.8.3	Mechanical improvement	43
2.8.4	Chemical stabilization	43
2.8.4.1	Lime stabilization	43
2.8.4.2	Cement stabilization	44
2.8.4.3	Fly ash stabilization	44
2.8.4.4	Other chemical admixtures	45
2.9	Stabilization of expansive soil using reinforcement	45
2.10	Reduction swelling of expansive clay using granular pile anchors.....	45
CHAPTER 3: FIELD MODELLING, INSTRUMENTATION, AND MONITORING		49
3.1	Forward	49
3.2	Site selection and subsurface investigation	49
3.3	Geotechnical characterization of clayey shale.....	53
3.4	Model and construction sequence	55
3.4.1	Model description	55
3.4.2	Construction sequence	58

3.5 Instrumentation and monitoring of model slab	63
3.5.1 Survey works	63
3.5.2 Strain gages	63
3.5.3 Earth pressure cell	64
3.5.3.1 Cell installation and preliminary tests	66
3.5.3.2 Pressure calculation theory	66
3.6 Field activities and monitoring results.....	67
3.6.1 Swell pressure measurements	67
3.6.2 Upward movement of field slab-on-grade models	67
3.6.3 Force in anchors	70
3.6.4 Strain measurements due to swelling effect	72
CHAPTER 4: NUMERICAL MODELLING	73
4.1 Forward	73
4.2 Finite element approach	73
4.2.1 General model description	73
4.2.2 Constitutive models and material parameters	75
4.2.3 Idealization of model	76
4.2.4 Modeling phases	79
4.3 Verification finite element model of GPAF and CPAF systems	80
4.4 Sensitivity analysis for GPAF system	83
4.4.1 Double GPAF System	84
4.4.2 Single GPAF System	86
4.5 GPAF design chart for Tabuk city	91
CHAPTER 5: SUMMARY AND CONCLUSIONS.....	94
References	97

List of Tables

Table 2.1 : Particle clay minerals properties	6
Table 2.2 : Soil expansivity prediction by liquid limit	8
Table 2.3 : Soil expansivity prediction by plasticity index	8
Table 2.4 : Soil expansivity prediction by shrinkage limit	9
Table 2.5 : Soil expansivity prediction by shrinkage index	9
Table 2.6 : Soil potential after Chen 1988.....	11
Table 2.7 : Soil potential after Bekkouch et al. 2001.....	12
Table 2.8 : Probable volume change for expansive soils	12
Table 2.9 : Classification for shrink–swell clay soils	12
Table 2.10 : Identification of swell potential based on plasticity index.....	13
Table 2.11 : Atterberg limits of clay minerals	14
Table 2.12 : Soil expansivity classification based on MFSI	17
Table 2.13 : Expansion potential from Expansion Index after UBC Code	19
Table 2.14 : CEC values for some clay minerals	19
Table 2.15 : Estimation of clay mineralogy using (COLE)	21
Table 2.16 : Ranges of COLE to determine soil swell-shrink potential	21
Table 2.17 : Prediction of swell percent (Schneider and Poor, 1974)	33
Table 2.18 : Effect of fly ash on swelling characteristics	44
Table 3.1 : Physical properties of natural soil at slabs on-grade location	54
Table 3.2 : Strain, stress and uplift forces in concrete pile anchor steel bar	71
Table 4.1 : Material properties of soil layers	76
Table 4.2 : Material properties of plate and anchor elements	78
Table 4.3 : Material properties of CPA	79
Table 4.4 : Effect of GPA on footing uplift displacement	88
Table 4.5 : Effect of GPA on anchor axial force	90
Table 4.6 : Summary of GPAF finite element models for design chart	92

List of Figures

Figure 2.1: Expansive soil distribution in over the world	3
Figure 2.2: Distribution of expansive soil in kingdom of Saudi Arabia	4
Figure 2.3: Plot of clay minerals on Casagrand's chart	9
Figure 2.4: Identification of swelling and slumping soils	10
Figure 2.5: Chart for potential expansiveness of soils.....	10
Figure 2.6 : Clay activity zones	11
Figure 2.7: Swell potential as function of colloids content and activity	15
Figure 2.8: Soil swell potential based on size fraction and activity	15
Figure 2.9: Van der merwe's zones of swell potential of soil	16
Figure 2.10 : Swelling potential of clayey soils due to CEC and LL values	20
Figure 2.11 : Distribution of samples, having various CEC value on the swelling potential chart of van der Merwe (1964)	20
Figure 2.12 : $e - \log P$ curve in a (ISO) test	23
Figure 2.13 : $e - \log P$ curve in a (SO) test	23
Figure 2.14 : $e - \log P$ curve in a (CVS) test	24
Figure 2.15 : Swell index vs. potential volume change	25
Figure 2.16 : Relationship between soil suction and water content	26
Figure 2.17 : Simplified oedometer test analysis (After Jennings et al., 1973) ...	27
Figure 2.18 : Laboratory relationship between void ratio and effective pressure..	28
Figure 2.19 : Void ratio versus water content (After Hamberg, 1985)	30
Figure 2.20 : Relationships for determining (a) Plasticity index (P.I) and (b) Reduction factor (P) for Van Der Merwe's empirical heave prediction methods	32
Figure 2.21 : Polygonal pattern of surface cracks in the dry season	35
Figure 2.22 : Effect of soil swelling action on ground beam	35
Figure 2.23 : Widening in construction joint	36
Figure 2.24 : Cracks in masonry walls	36
Figure 2.25 : Grade beam and pier system	38
Figure 2.26 : Typical schematic drawing of stiffened raft	39
Figure 2.27 : Profiles after construction for various stiffness of raft	40
Figure 2.28 : Monolithic slab system	41
Figure 2.29 : Schematic diagram for sand cushion / CNS layer	42
Figure 2.30 : Effect of lime percentage and curing time on the swell pressure ...	44
Figure 2.31 : Effect of chemical additive percent on free swell of expansive soil	45
Figure 2.32 : Concept of granular pile anchor foundation system	46

Figure 3.1	: Testing area location	49
Figure 3.2	: Damage in fence beside the testing area	50
Figure 3.3	: Pavement cracks beside the testing area	50
Figure 3.4	: Sub-surface layers log (middle boring, BH-1)	51
Figure 3.5	: Geological profile around testing area	52
Figure 3.6	: Grain size distribution	53
Figure 3.7	: Swell – Consolidation test	55
Figure 3.8	: Schematic section for slab on grade	56
Figure 3.9	: Schematic section of GPAF system	57
Figure 3.10	: Schematic section of CPAF system	58
Figure 3.11	: Field testing area excavation	59
Figure 3.12	: Preparation of slab-on-grade location.....	59
Figure 3.13	: Anchors holes drilling and cleaning	60
Figure 3.14	: Granular anchor pile (GPA) installation	61
Figure 3.15	: Earth pressure cell installation	61
Figure 3.16	: Strain gages installation	62
Figure 3.17	: Casting of slab-on-grade models	62
Figure 3.18	: Field slab-on-grade model	63
Figure 3.19	: Strain gages arrangements at CPAF model	64
Figure 3.20	: Earth pressure cell components	65
Figure 3.21	: Readout unit connection with gage cable	65
Figure 3.22	: Measurements of swelling pressure by earth pressure cell during test period	67
Figure 3.23	: Distribution of surveying fixed points	68
Figure 3.24	: Upward displacement of fixed points on slab-on-grade.....	68
Figure 3.25	: Upward displacement of fixed points of GPAF model	69
Figure 3.26	: Upward displacement of fixed points of CPAF model	69
Figure 3.27	: Effect of pile anchor type on slab-on-grade displacement	70
Figure 3.28	: Strain gages measurements in CPAF slab model	71
Figure 3.29	: Strain gages measurements of reinforcement steel bars of CPAF model	72
Figure 4.1	: Profile view of geometry model	74
Figure 4.2	: Descriptive finite element model of GPAF system	74
Figure 4.3	: Descriptive finite element model of CPAF system	75
Figure 4.4	: Finite element mesh of GPAF system	77

Figure 4.5: Stiffness matching procedure for CPA from 3D to 2D	78
Figure 4.6: Descriptive sketch of GPAF geometry model in Plaxis window	80
Figure 4.7: Uplift displacement of GPAF model	81
Figure 4.8: Geometry deformed shape around the plate elements and anchor axial force (GPAF model)	81
Figure 4.9: Stresses distribution in GPAF finite element model	81
Figure 4.10 : Bending moment distribution in GPAF finite element model	82
Figure 4.11 : Uplift displacement of CPAF model.....	82
Figure 4.12 Model section of GPAF system supported on single or double GPA	83
Figure 4.13 : Effect of single GPA length on the uplift displacement GPAF model with time (GPA equivalent thickness 20cm)	84
Figure 4.14 : Effect of single GPA length on the uplift displacement GPAF model with time (GPA equivalent thickness 30cm)	85
Figure 4.15 : Effect of length and diameter of GPA on the maximum bending moment of footing in GPAF finite element model	85
Figure 4.16 : Descriptive sketch of footing supported on a single GPA	86
Figure 4.17 : Effect of single GPA length on GPAF model uplift displacement with time (GPA equivalent thickness 20 cm).....	87
Figure 4.18 : Effect of single GPA length on GPAF model uplift displacement with time (GPA equivalent thickness 30 cm).....	87
Figure 4.19 : Effect of GPA length on footing upward displacement	88
Figure 4.20 : Effect of GPA length on footing bending moment infinite element modeling	89
Figure 4.21 : Effect of GPA on axial force resistance	90
Figure 4.22 : GPAF geometry model section for design chart	91
Figure 4.23 : Design chart for heave prediction of footing supported on double GPA at Tabuk city	92
Figure 4.24 : Design chart for heave prediction of footing supported on a single GPA at Tabuk city	93

List of Abbreviations:

A: Clay activity
C: Clay content
e: Void ratio
E: Young's modulus
 ϵ : Strain
S: Swelling potential
 P_s : Swelling pressure
 C_s : Swelling Index
LL: Liquid limit
PI: Plasticity index
PL: Plastic limit
SL: Shrinkage limit
SI: Shrinkage index
EI: Expansion index
 P_{ov} : Over burden pressure
 S_p : Predicted swell percentage
FSI: Free swell index
CEC: Cation exchange capacity
GPA: Granular pile anchor
CPA: Concrete pile anchor
GPAF: Granular pile anchor foundation system
CPAF: Concrete pile anchor foundation system
MFSI: Modified free swell index
COLE: Coefficient of linear extensibility

ABSTRACT

Expansive soils in Saudi Arabia regions, such as Tabuk, Tymaa, Tabarjal, and Al Madina, have received wide attention in recent decades. This type of soil causes many problems and cracks in most structures and roads, which are constructed on it. The research is aimed at studying the performance of reinforced concrete slab which constructed on expansive soils at Tabuk city. The soil engineering properties were determined and compared with the soil which was classified as laminated weathered shale (CH). The swelling pressure and free swell index were 120 kPa and 105% respectively.

One of the techniques that are used to control the severity of distress caused to structures founded on expansive soils is the granular pile anchor foundation system (GPAF). It reduces heave behavior and improving the engineering behavior of expansive clay. Another technique is filling the pile holes by fresh concrete called in this research concrete pile anchor foundation system (CPAF). In this research, three full scale models have dimensions of (2.0 x 2.0 x 0.4 m) are constructed in-situ and tested as follow:

- 1- First slab is constructed directly on natural soil as a regular footing.
- 2- Second slab is constructed using GPAF system. The granular pile anchor (GPA), have length of 2.0 m and 20 cm diameter.
- 3- Third slab is founded on concrete pile anchors foundation (CPAF) connecting the slab-on-grade into the subsurface soil with 2.0 m length and 20 cm diameter concrete piles.

The field models are constructed to evaluate the efficiency of the granular pile anchor foundation (GPAF) system compared to the concrete pile anchor foundation (CPAF) system in reducing heave of slab-on-grade, resulting from the expansive soils. Field models site area is submerged with water for a period of 64 days. One borehole is drilled by compressed air to investigate the maximum depth of saturation measured during this period. Also, the maximum volumetric strain occurred in the saturated clay layer is determined. An earth pressure cell is fixed in contact with soil beneath center of GPAF model. At the end of test period, the measured field swelling pressure is 49 kPa. Due to the swelling action of expansive soil, the measured uplift displacement of three full scale models are 125 mm, 54 mm, and 47 mm, respectively. Stiffening the slab rested on expansive soil using granular pile anchors (GPA) or concrete pile anchors (CPA) are reduced the upward movement by 57%, and 62%, respectively. From the field measurements of swelling pressure, the force resisted by the Granular Pile Anchor was measured. Strain gages were installed on steel reinforcement steel bars of CPAF slab model and top of concrete pile anchor steel bar, it aimed at measuring the strains happened due to the soil swelling action and to determine the force resisted by the concrete pile anchors.

Finite element modeling is used to predict the heave of GPAF and CPAF models. PLAXIS 2D-Version 8.2 program is used in numerical modeling and analysis of the tested heave problems. The problem deals with footing have same characteristics of field model rested on expansive soil supported on GPA or CPA. The active zone of the expansive soil is similar to the wetted depth in the field models. A verification model is constructed to simulate observations in the field. In Plaxis model, definition of expansive soil is made by applying volume strain to the wetted surface layer with positive value. The obtained results of footing uplift displacement for three models are

55.6 mm for GPAF model, and 46.9 mm for CPAF model. Therefore, there is a good agreement between field observation data and finite element analysis. In addition, the model has been used to make sensitivity analysis as other finite element models are simulated for GPAF system to study the effect of pile diameter; depth and number on the foundations heave behavior. Finally, a design chart is presented to predict the heave that may be occurred for foundations at Tabuk city, kingdom of Saudi Arabia