Analysing Ground Deformation Data to Predict Characteristics of Smear Zone Induced by Vertical Drain Installation for Soft Soil Improvement

A thesis in fulfilment of the requirement
for the award of the degree

Doctor of Philosophy

from

University of Technology, Sydney

by

Ali Parsa-Pajouh, BSc Eng, Msc Eng

School of Civil and Environmental Engineering,
Faculty of Engineering and Information Technology

February 2014

CERTIFICATION

I, Ali Parsa-Pajouh, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Department of Civil and Environmental Engineering, University of Technology, Sydney, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualification at any other academic institution.

Ali Parsa-Pajouh

February 2014

DEDICATION

This work is sincerely dedicated to the following special people:

To My Lovely Wife, Neda

For her endless encouragement and patience, without her love and support, I could have never completed this journey.

To My Father, Davoud

He was my role-model of hard work, persistence and personal sacrifices. He inspired me how to be strong, how to be honest.

To My Late Beloved Mother, Maryam

For all the sacrifices she has made to ensure that I obtain the best education possible, for her beautiful mind and unconditional love.

ABSTRACT

The use of prefabricated vertical drain (PVD) assisted preloading has been recognised over the last two decades as a very efficient method of ground improvement for sites with deposits of deep soft soil. One of the major parameters influencing the PVD assisted consolidation process, and consequently the required preloading time, is the formation of a smear zone around the vertical drains, and the corresponding soil properties. In this research a systematic procedure integrated with a developed numerical code is proposed to accurately back calculate the properties of the smear zone based on the consolidation data collected in the laboratory and in the field. Furthermore, an expanded back calculation method is developed to determine the minimum required degree of consolidation and corresponding time after the construction of the trial embankment that would result in accurately predicted smear zone characteristics. The explicit finite difference program FLAC 2D was used to develop the numerical code, simulate the laboratory testing and PVD assisted preloading case histories. Furthermore a comprehensive parametric study was conducted to investigate the effect of smear zone properties variations on the preloading process, and back calculated characteristics of the smear zone.

A large and fully instrumented Rowe cell apparatus was used to investigate the effect of the smear zone on the consolidation process and verify the developed numerical code. The Rowe cell was filled with the intact zone, smear zone, and vertical drain materials to evaluate the permeability and extent ratios of k_h/k_s=4 and r_s/r_m=3, respectively. The back calculation procedure was used to conduct the parametric study and predict the properties of the smear zone. According to the results, the predicted properties of the smear zone were similar to the properties of the applied soil, proving that the proposed back calculation procedure integrated with the developed numerical simulation can successfully predict these properties.

The developed numerical code was used to simulate five PVD assisted preloading case studies, including four trial embankments and a large scale consolidometer, while the back calculation procedure was used to conduct a parametric study to determine the extent and permeability of the smear zone. According to the results, integration of the back calculation procedure in the

numerical code can be used as a reliable tool to make an accurate prediction of the smear zone characteristics in PVD and vacuum assisted preloading projects.

The developed method in this research can be considered as a practical, accurate and cost effective tool, due to its capability in precise estimation of the extent and permeability of the smear zone in the early stages of constructing the trial embankment. In this study, the proposed systematic back calculation procedure was extended to determine the minimum degree of consolidation (i.e. the minimum waiting time after constructing the trial embankment), and accurately predict the properties of the smear zone. The numerical results of the simulated case studies were used to conduct the analyses. Accordingly, it is found that the extent and permeability of the smear zone can be predicted very well with the proposed calculation procedure when at least 33% of predicted final settlement has been reached (i.e. 33% of the degree of consolidation).

ACKNOWLEDGEMENT

Working as a PhD student at University of Technology, Sydney was a magnificent as well as challenging experience to me. In all these years, many people were involved directly or indirectly in shaping up my academic achievements. It was hardly possible for me to succeed in my doctoral work without the precious support of these kind personalities. Here is a small tribute to all those people.

First of all, I would like to express my deepest gratitude to my supervisor, Dr. Behzad Fatahi for his brilliant guidance, caring, patience, and providing me with an excellent atmosphere for doing research. It has been an honour to be his first PhD student. His numerous comments, criticisms and suggestions during the preparation of this thesis are gratefully acknowledged.

I would like to thank my co-supervisor, A/Prof. Hadi Khabbaz, who was abundantly helpful and offered invaluable assistance, support and guidance. His encouragement, support and critical review of the thesis, as well as his comprehensive suggestions at various stages of this study are greatly appreciated. I would also like to acknowledge Bill Clayton for his critical review of the thesis and helpful comments.

My appreciation is also extended to UTS laboratory and workshop staff Antonio Reyno and Laurence Stonard as well as the PhD students Babak Azari, and Thu Minh Le for their valuable assistance and contribution in running and conducting the laboratory test. I am also thankful to University of Technology, Sydeny and its staff for their financial, academic and technical support. The library and computer facilities of the University have been indispensable. I very much appreciate the Centre for Built Infrastructure Research (CBIR), particularly, Prof. Bijan Samali for their support and assistance since the start of my PhD study.

I gratefully acknowledge the funding sources that made my PhD work possible. This research was funded by Australian Research Council and supported by the Menard-Bachy Pty Ltd as the industry partner, which are so appreciated.

I would also like to acknowledge Road and Maritime Services (RMS) for providing the field measurements and site investigation results for Ballina Bypass and Cumbalam trial embankments.

I have been in charge of tutoring different subjects in last four years, which was a priceless experience for me. I would like to take this opportunity to express my special gratitude towards academic staff of the School of Civil and Environmental Engineering, Dr. Behzad Fatahi, A/Prof. Hadi Khabbaz, Dr. Shami Nejadi, Dr. Rezaul Karim, Anne Gardner, Chris Wilkinson and Dr. Rijun Shrestha, who supported me in this journey.

Gratitude is also expressed to my friends and fellow students at the University of Technology, Sydney, particularly, Amir Zad, Babak Azari, Behnam Fatahi, Binod Shresta, Hamid Tabatabaei, Thu minh Le and Yashar Maali for keeping the study atmosphere enjoyable and pleasant.

I would like to express heartfelt acknowledgement to my wife, Neda Khodadoust, for her constant love, sacrifices, support, encouragement, and patience. She was always there cheering me up and stood by me through the happy and hardships times. Without her guidance and support, I may never have come this far in my study.

Lastly, I would like to thank my parents, who raised me with a love of science and supported me in all my pursuits. Special thanks to my two elder sisters, and my younger brother, who were always supporting and encouraging me with their best wishes.

TABLE OF CONTENT

4. LABORATORY STUDY TO INVESTIGATE THE SMEARING EFFECT ON THE PERFORMANCE OF PVD ASSISTED PRELOADING

5. CASE STUDIES AND FURTHER VALIDATION EXERCISES

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

a_o	initial radius of cavity
B	equivalent plane-strain radius of the influence zone
BP	back Pressure
b_s	equivalent plane-strain radius of the smear zone
b_w	equivalent plane-strain radius of the drain
C_c	compression index
C_f	hydraulic conductivity ratio between the field and laboratory values
CP	cell Pressure
Cs	swelling index
c'	cohesion in drained condition
c_f	hydraulic conductivity ratio between field and laboratory values
c_h	coefficient of horizontal consolidation
c_k	permeability change index
c_v	vertical coefficient of consolidation
c_{vc}	coefficient of consolidation for the combined vacuum and surcharge preloading
D_{10}	effective particle size
D_{15}	grain diameter at 15% passing
D_{30}	grain diameter at 30% passing
D_{50}	grain diameter at 50% passing
D_{60}	grain diameter at 60% passing
D_{85}	grain diameter at 85% passing
DL	data logger
dc	diameter of unit cell
de	equivalent drain diameter
d_m	mandrel diameter
d_s	smear zone diameter
d_w	diameter of drain
E	Young’s modulus
E_f	final cumulative error
$(E_f)_i$	cumulative error at step i

$(E_f)_s$	corresponding cumulative error to the extent ratio s
E_i	error between numerical predictions and field measurements at step i
$(E_{min})_s$	minimum error corresponding to step s
$(E_t)_n$	normalised cumulative error at time t and step number n
$(E_t)_n$	normalised cumulative error at time t and step number n
$(E_{U\%})_i$	corresponding error to U% at step i
$(E_{U\%})_{min}$	minimum error
$(E_{U\%})_s$	corresponding error to the extent ratio s
EPWP	excess pore water pressure
e	void ratio
e_{cs}	void ratio at the critical state
e_o	initial void ratio
F_k	field measurements
F_s	reduction factor
G	shear modulus
G_s	Specific garvity
g_i or g_k	gravity vector
H_d	vertical drainage length
I_r	normalised by the rigidity index
IVC	definite volume controller
K_w	water bulk modulus
k	coefficient of isotropic mobility
$(k_h/k_s)_i$	permeability ratio at step i
$(k_h/k_s)_{max}$	maximum permeability ratio
$(k_h/k_s)_{min}$	minimum permeability ratio
$(k_h/k_s)_o$	assumed initial permeability ratio
$(k_h/k_s)_{opt}$	predicted permeability ratio at $U\%_{min}$
$(k_h/k_s)_s$	permeability ratio corresponding to step s that gives the minimum error
$\hat{k}(s)$	relative permeability
k_1	ratio between the vacuum pressure at the top and bottom of the drain
$k_{e,ax}$	equivalent horizontal permeability for the axi-symmetric unit cell

$k_{e,pl}$	equivalent horizontal permeability for the plane-strain unit cell
k_{ep}	horizontal permeability coefficient in the equivalent zone of plane-strain unit
k_f	permeability of the filter
k_h	intact zone horizontal permeability
k_h/k_s	permeability ratio
k_{hp}	horizontal permeability of intact zone in plane-strain condition
k_{ij}	tensor of the coefficient of permeability
k_s	smear zone permeability
k_{sp}	horizontal permeability of smear zone in plane-strain condition
k_v	intact zone vertical permeability
k_{ve}	equivalent coefficient of vertical permeability
k_w	coefficient of permeability of PVD
LL	liquid limit
LVDT	linear vertical displacement Transducer
l	drainage length
l_m	the length of the vertical drain
$[\mathcal{M}]$	stiffness matrix
M_b	biot modulus
M	slope of the critical state line
MCC	modified cam clay
N	total number of observation points
n	porosity
$n = R/r_w$	ratio of the influence radius to the drain radius
$n = k_h/k_s$	permeability ratio
n_p	isotropic over consolidation ratio
O_{50}	opening size of the filter which is larger than 50% of the fabric pore
O_{95}	the apparent opening size of the filter
OCR	over consolidated ratio
P/V C	pressure/volume controller
PL	plastic limit
PVD	prefabricated vertical drain

PWPT	pore water Pressure Transducer
p'	mean effective stress
P'_1	reference pressure
P'_c	preconsolidation pressure
PI	plasticity index
P_k	numerical predictions
p_o	initial mean pressure
p'_o	initial effective mean pressure
P_{vo}	vacuum pressure applied at the top of the drain
p'_{y_o}	maximum isotropic preconsolidation stress
$\{Q\}$	nodal flow rate
q	deviator stress
q_i	specific discharge vector
q_{req}	required discharge capacity
q_v	intensity of the volumetric water source
q_w	discharge capacity of PVD
q_{wp}	equivalent plane-strain discharge capacity
R	radius of the influence zone
$(r_s/r_m)_i$	extent ratio at step i
$(r_s/r_m)_{max}$	maximum extent ratio
$(r_s/r_m)_{min}$	minimum extent ratio
$(r_s/r_m)_o$	assumed initial extent ratio
$(r_s/r_m)_{opt}$	predicted extent ratio at $U\%_{min}$
$(r_s/r_m)_s$	extent ratio corresponding to step s that gives the minimum error
r_1	instantaneous radius of an elliptical cavity
r_m	mandrel radius
r_o	initial radius (in the direction of the semi-major axis) of an elliptical cavity
r_p	radial distance of the plastic zone around the cavity
r_s	smear zone radius
r_s/r_m & r_s/r_w	extent ratio
r_{tr}	radius of transition zone

r_w	drain radius
S	drain spacing (centre to centre)
S_f	final primary consolidation settlement
S_{pr}	field settlement at the end of preloading time
S_t	field settlement at time t
S_{tp}	predicted settlement at time t
s	extent ratio (r_s/r_w) or (r_s/r_m)
T_{hp}	radial consolidation time factor
T_r or T_h	radial consolidation time factor
T_v	vertical consolidation time factor
T_{vc}	time factor for the combined vacuum and surcharge preloading
$t_{90\%}$	corresponding time at 90% degree of consolidation
t_{min}	corresponding consolidation time to the $U\%_{min}$
t_{pr}	preloading time
$\overline{U}$	total degree of consolidation in plane-strain condition
$U\%$	degree of consolidation at time t
$U\%_{min}$	minimum required degree of consolidation
$U\%_n$	degree of consolidation at step n
$\overline{U}_h$	average degree of radial consolidation in axi-symmetric condition
$\overline{U}_{hp}$	average degree of radial consolidation in plane-strain condition
$U_{pr}\%$	degree of consolidation at the end of preloading
$\overline{U}_v$	average degree of vertical consolidation
u_o	initial excess pore water pressure
V	total volume associated with the node
w	water Content
z	depth

Greek Letters

α	biot's coefficient
β	pore pressure coefficient
γ_q^p	plastic shear strain
γ_s	unit weight
ΔR	permeability ratio incremental rate

ΔS	extent ratio incremental rate
ΔV_{mech}	equivalent increase in the nodal volume arising from mechanical deformation of the grid
$\Delta\sigma_{oct}$	octahedral normal stress
$\Delta\tau_{oct}$	octahedral shear stress
ϵ	volumetric strain
ζ	ariation of water volume per unit volume of porous material
η	stress ratio
κ	slope of the specific volume versus ln(p') curve for swelling
Λ	plastic volumetric strain ratio
λ	slope of the specific volume versus ln(p') curve for compression
μ	Poisson's ratio
ν	specific volume
ν_λ	specific volume at the reference pressure
ρ_d	bulk density of the dry matrix
ρ_s	density of the solid phase
ρ_w	mass density of the water
σ_c	the lateral pressure
σ_o	initial cavity internal pressure
σ_r	total stress
σ_{rp}	total radial stress at the elastic-plastic boundary
φ'	friction angle in drained condition