Three-Dimensional Numerical and Physical Modelling of Soft Soil Improvement Using Concrete Injected Columns

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by

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Hamed Mahdavi

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To My Family

ABSTRACT

Concrete injected columns (CICs) are a popular method for improving soft soil properties to support road and bridge approach embankments due to quick construction, absence of spoil, and limited post-construction settlement. While the limited settlement of CICs makes them attractive for cases where there are stringent settlement criteria, low-cost methods of improving soils are used where there are no such limitations. The lack of comprehensive experimental studies on CICs in the available literature showed the necessity of further laboratory modelling. Moreover, the equivalent comparison between frictional and socketed CICs has not been thoroughly studied.

In this study, a well-instrumented physical modelling of soft clay improved with CICs was performed. A granular layer was used to model the load transfer platform (LTP), and a geotextile layer was utilised to model the geosynthetic reinforcement (GR) layer. The load was applied and controlled in stages using a large loading frame on top of the granular layer. Pore pressure dissipation, stresses transferred to the soft soil and CICs, and the strains in the geotextile were monitored with time. A three-dimensional numerical model was also developed using finite difference software FLAC^{3D}, and the results were validated against the experimental data. The numerical model considered coupled flow-deformation allowing prediction of the excess pore water pressure (EPWP) dissipation with time, while the permeability of the soft soil varied with time. Modified Cam-Clay (MCC) soft soil model was used as the constitutive model for the soft clay deposit, while elastic-perfectly plastic Mohr-Coulomb failure criterion was used to simulate the LTP layer. Hoek-Brown constitutive model was used to model the unreinforced concrete used for CIC construction. A good agreement was perceived between the numerical results and the

measurements from the experiment. Referring to both measurements and predictions, despite the low permeability of the soft clay, a rather quick dissipation in the EPWP occurred due to the load transfer mechanism between the soft soil and CICs. The stress concentration ratio decreased at the beginning of the loading stages and then later increased with time, and was higher for higher applied loads.

This thesis also sets out to investigate the options available for the transition zone from CICs to other ground improvement methods away from the abutment. Two possible alternatives were numerically simulated using FLAC^{3D} software considering the dissipation of pore water pressure and variation of soil permeability with time. A geosynthetic layer was introduced into the load transfer platform (LTP) located above the CICs, and interface elements were incorporated to simulate CIC-soil interaction. The first option for the transition zone was widely spaced CICs socketed into stiff material and the second was using shorter, closely spaced, frictional CICs. A comparison was then made between the predicted ground settlement, the force mobilised in the geosynthetic, the excess pore water pressure, and stresses in the CICs for the two scenarios. The total length of the CICs and thus the total volume of the concrete used for their construction were kept the same for both alternatives. Indeed, the embankment on frictional CICs experienced less settlement, the forces mobilised in the geosynthetic were reduced, and the bending moments and shear forces generated in the columns were less than the corresponding values for the case of socketed CICs. This study showed that for a given volume of concrete, shorter, frictional CICs perform better than longer CICs socketed into stiff strata.

Furthermore, a comparison was made between drained and coupled flow-deformation numerical analyses. This study revealed that while performing drained analysis by simply assigning drained parameters to the material was less computationally demanding, it lead to inaccuracies in the predictions. The perceived discrepancies were attributed to the difference in the stress-path of drained and coupled analyses.

The results from this study can be beneficial for the practicing engineers for designing structures on CIC-improved grounds, particularly for predicting the time-dependent performance of the system.

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LIST OF PUBLICATIONS

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2. Mahdavi, H., Fatahi, B., Khabbaz, H., 2018. "A Comparison of Frictional and Socketed Concrete Injected Columns in a Transition Zone." Submitted to *Geosynthetics International*

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4. Mahdavi, H., Fatahi, B., Khabbaz, H., Krzeminski, M., Santos, R. and Marix-Evans, M., 2016. "Three-Dimensional Simulation of a Load Transfer Mechanism for Frictional and End-Bearing CMC-Supported Embankments on Soft Soil." In *Geo-China 2016*, pp. 60-67

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a	Pile cap width
A_r	Area replacement ratio
c'	Effective cohesion
C_k	Slope of the logk-e graph
c_u	Undrained shear strength of the soft soil
D	Inclusion diameter
d_{LTP}	Average size of the LTP granular material
e	Void ratio
E	Elastic modulus
e_0	Reference void ratio/Initial void ratio
E_c	Elastic modulus of the CIC material
E_{LTP}	Elastic modulus of the LTP material
E_s	Elastic modulus of the soft soil
f_c'	Characteristic compressive (cylinder) strength of concrete
f_{cmi}	Mean value of the in situ compressive strength of concrete
f'_{ct}	Characteristic uniaxial tensile strength of concrete
F_N	Resultant of negative friction
G	Shear modulus
H	LTP height
h_a	Height of the upper plane of equal settlement
h_c	Height of negative friction action taking place in the soft layer (critical height)
H_m or H_M	Platform height
h_r, h_a	Height of negative friction application on the fictitious column positioned on top of the inclusion head
I	Area moment of inertia
J	Geosynthetic stiffness
K	Bulk modulus
k	Permeability
K_0	Coefficient of lateral earth pressure at rest
$K_{0(NC)}$	Lateral earth pressure coefficient at rest for normally consolidated soils
$K_{0(OC)}$	Lateral earth pressure coefficient at rest for over-consolidated soils
K_a	Coefficient of active earth pressure
k_i	Reference permeability
k_n	Interface normal stiffness

K_p	Coefficient of passive earth pressure
k_s	Interface shear stiffness
L	CIC length
m	Exponent capturing the increase in strength due to preconsolidation
M	Critical state stress ratio
n	Porosity
N	Scaling factor
n_s	Stress concentration ratio
p_0	Uniform pressure applied on the geosynthetic
p'_c	Preconsolidation pressure
Q_p	Vertical net force of loads applied at the head of an inclusion
q_s^+	Stress applied on the soft soil (without an inclusion)
Q_{Ult}	Ultimate bearing capacity of the CIC-supported ground
R_c	Interface interaction coefficient for soil-CIC
R_G	Interface interaction coefficient for geotextile-LTP
R_{int}	Coeffiecient for interface strength reduction
r_p	Inclusion radius
s	Hoek-Brown constant
S	CIC spacing
S_u	Shear strength of soil
t	Geosynthetic thickness
T	Tension in the geosynthetic
T_{ult}	Tensile strength of the geosynthetic
u	Pore water pressure
V	Initial specific volume
W_p	Weight of the load platform supported by an inclusion head in a unit cell

Greek Symbols

α_L	Scaling factor for length
α_T	Scaling factor for geosynthetic tensile strength
α_σ	Scaling factor for stress
γ	Unit weight
γ_c	Unit weight of the CIC material
γ_{dry}	Dry unit weight
γ_{LTP}	Unit weight of the LTP soil
γ_r	Unit weight of the embankment
γ_s	Unit weight of the soft soil
ε	Strain

κ	Slope of elastic swelling line
λ	Slope of normal consolidation line
ρ	Density of the concrete
σ'	Effective stress
σ_1	Major principal effective stress
σ_3	Minor principal effective stress
σ_c	Stress on the inclusion
σCS	Uniaxial strength of the concrete
σ_M	Extreme stress due to bending
σ_N	Axial stress in CIC
σ_s	Stress on soil
σ_v	Total vertical stress
σ_v'	Effective vertical stress
σ_v*	Average effective vertical stress within a horizontal cross-section
υ	Poisson's ratio
ϕ	Friction angle
ϕ'	Effective friction angle
φ'_{LTP}	Angle of internal friction for LTP material
Ψ	Dilation angle

LIST OF ABBREVIATIONS AND ACRONYMS

2D	Two-dimensional
3D	Three-dimensional
CIC	Concrete Injected Columns
DL	Data logger
DT	Data taker
EPC	Earth pressure cells
EPWP	Excess pore water pressure
GRCS	Geosynthetic-reinforced column-supported
KBS	Kaolin-Bentonite-Sand
LC	Load cell
LTP	load transfer platform
LVDT	Linear variable differential transformer
MCC	Modified Cam-clay
MT	mobile tray
PWPT	Pore water pressure transduecer
SCR	Stress Concentration Ratio
SG	Strain Gauge
SRR	Stress reduction ratio