Effects of Installation Sequence of Concrete Rigid Inclusions by Ground-Displacement Piling Method on Previously Installed Columns

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Certificate of Original Authorship

I, **Huu Hung Nguyen**, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This research is supported by an Australian Government Research Training Program Scholarship.

Signature: Production Note: Signature removed prior to publication.

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List of Research Papers

The following technical papers were written during this research project:

- Nguyen, H.H., Khabbaz, H. & Fatahi, B. 2018, 'A Numerical Comparison of Installation Sequences of Plain Concrete Rigid Inclusions', **Computers & Geotechnics**, submitted 2 January 2018; accepted 2 September 2018, published online 21 September 2018, https://doi.org/10.1016/j.compgeo.2018.09.001.
- Nguyen, H.H., Khabbaz, H., Fatahi, B. & Kelly, R. 2016, 'Bridge Pile Response to Lateral Soil Movement Induced by Installation of Controlled Modulus Columns', **Procedia Engineering**, vol. 143, pp. 475-482, https://doi.org/10.1016/j.proeng.2016.06.060.
- Nguyen, H.H., Khabbaz, H., Fatahi, B. & Hsi, J. 2017, 'Effects of installing controlled modulus columns on previously installed columns', the **19th International Conference on Soil Mechanics and Geotechnical Engineering** - Seoul, South Korea, , pp. 2611-2614, https://www.issmge.org/publications/online-library.
- Nguyen, H.H., Khabbaz, H., Fatahi, B., Santos, R., Marix-Evans, M. & Vincent, P. 2016, 'Installation Effect of Controlled Modulus Columns on Nearby Existing Structures', **Geochina International Conference** 2016, vol. GSP 264, pp. 125-133, https://ascelibrary.org/doi/10.1061/9780784480076.015.
- Nguyen, H.H., Fatahi, B. & Khabbaz, H. 2014, 'Challenges in assessing the installation effects of controlled modulus columns on behaviour of surrounding soils', **The Fourth International Conference on Géotechnique, Construction Materials and Environment**, Brisbane, Australia, pp. 44-49.
- Nguyen, H.H., Khabbaz, H., Fatahi, B., Vincent, P. & Marix-Evans, M. 2014, 'Sustainability considerations for ground improvement technique using controlled

modulus columns', **Australian Geomechanics Society,** "Resilient Geotechnics", Sydney Australia, pp. 170 - 184.

- Nguyen, H.H., Khabbaz, H. & Fatahi, B. 2018, 'Model Test on the Responses of Early Age Concrete Inclusions in Soft Ground Subject to Nearby Installations', Canadian Geotechnical Journal (in preparation).
- Nguyen, H.H., Khabbaz, H. & Fatahi, B. 2018, 'Effects of Pile Penetration in Comparison with Combined Cylindrical and Spherical Cavity Expansions: Experimental and Numerical Studies', International Journal of Geomechanics (in preparation).

Huu Hung Nguyen, Behzad Fatahi and Hadi Khabbaz received the award of the best paper for their paper titled: *'Challenges in assessing the installation effects of controlled modulus columns on behaviour of surrounding soils'*, presented in The Fourth International Conference on Géotechnique, Construction Materials and Environment, Brisbane, Australia in November 2014.

Abstract

Ground improvement techniques using concrete injected column (CIC) or controlled modulus column (CMC) have been widely used since 1980s. However, impacts of ground displacement induced by the techniques have not been studied adequately. This project advances both experimental and numerical bases for assessing effects of installing CICs or CMCs on the surrounding soils and previously installed columns, with interests given to installation sequence and behaviour of concrete inclusion at early age.

Three-dimensional numerical modelling was conducted to investigate how groups of columns installed in different sequences could affect previously installed columns. The assessment included coupled consolidation analyses in large strain mode, considering soil-column interaction. CMC installation was modelled numerically with the combined use of cylindrical and spherical cavity expansion theories. Where possible, the results were compared with analytical solutions and published field cases. The study revealed that the use of different installation sequences resulted in noticeable differences in the soil responses near existing CMCs as well as the difference in the bending moments generated in the previously installed columns.

A soil-displacement piling rig and a fully instrumented soil tank were also designed and built in the laboratory to simulate column installations and to study the soil behaviour and the responses of previously built columns to nearby installations. A group of concrete columns were cast in-situ in soft soil using low strength concrete. The installation effects in terms of soil behaviours and structural responses of the columns were well captured by 3D laser scanning, soil miniature instrumentation, and a customised strain gauge system installed in CMCs. Test results revealed complex interactions between the soil and the columns, which are otherwise often difficult to observe in the field.

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The following symbols were used in this thesis:

Δu	excess pore water pressure
Δu_{sp}	excess pore water pressure due to spherical cavity expansion
$\Delta_{z,min}$	smallest width of *FLAC^{3D}* zone
δ	column lateral deflection
κ	swell-recompression index
λ	virgin compression index
ν'	soil's effective Poisson's ratio
ν'_c	Poisson's ratio of concrete
ρ_c	concrete density
ρ_d	dry density of soil
ρ_{sat}	soil saturated unit weight
σ'_1	major principal stress in CMC
σ'_3	minor principal stress in CMC
σ_c	unconfined compressive strength of grout specimen or intact concrete
σ_{st}	indirect tensile strength of grout specimen
σ_t	tensile strength of concrete
$\sigma'_{v,o}$	in-situ vertical effective stress
$\sigma'_{h,o}$	in-situ horizontal effective stress
υ	specific volume
υ_{ref}	reference specific volume
ϕ'_{cs}	soil's effective friction angle
ϕ'	effective friction angle
ϕ'_i	interface friction angle
ψ_c	dilation angle of concrete
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C_c	soil compression index
C_k	permeability change index
C_r	soil recompression index
c'	effective cohesion of soil
c'_i	interface effective adhesion
c_v	vertical coefficient of consolidation

D	CMC or column diameter
d_{pile}	pile diameter
E' or E_s	drained Young's modulus of soil
E_{c}	Young's modulus of concrete
e_o	initial (or current) void ratio
f_{ck}	characteristic cylinder strength of concrete at 28 days
f'_{ck}	characteristic cylindrical strength of grout at 28 days
$f_{\text{ck}}(\text{t})$	characteristic cylinder strength of concrete or grout at age of *t* days
$f_{\text{ctd,pl}}$	mean tensile strength of plain concrete (e.g. CMC)
f_{ctm}	mean tensile strength of concrete
$f_{\text{ctm (t)}}$	mean tensile strength of concrete at t days.
G	shear modulus of soil
G_{s}	specific gravity of soil
I	area moment of inertia
K	bulk modulus of soil
K_0	coefficient of earth pressure at rest
K_{f}	fluid bulk modulus
k *or* k_{h}	hydraulic conductivity of soil
k_{n}	interface normal stiffness
k_{o}	initial permeability
k_{s}	interface shear stiffness
L	column length
M	slope of the critical state line
M *or* $M(z)$	column bending moment
m	Hoek Brown material constant
N	constant in K_0 equation
n	porosity
OCR	over consolidation ratio of soil
p'	mean effective stress of soil
p'_c	pre-consolidation pressure of soil
p'_o	initial mean effective stress in the soil
p'_{ref}	reference pre-consolidation pressure (i.e. 1 kPa)
q	deviatoric stress
R	radial distance from column axis

R_p radial position of elastic-plastic boundary (cylindrical cavity)

R_{sp} radial position of elastic-plastic boundary (spherical cavity)

r_{CMC} CMC radius

r_{c} column radius

r_f radius of expanded cavity

r_i initial radius of cavity

r_{pile} radius of pile

S Hoek-Brown material constant

s column spacing

s_{c} coefficient taking into account the cement type

s_{u} undrained shear strength of soil

u_{max} maximum excess pore water pressure

$\mathrm{u_o}$ in-situ pore water pressure

V shear force in CMC

V *or* $\mathrm{v_{norm}}$ non-dimensional pile penetration velocity

$\mathrm{v_p}$ vertical pile penetration velocity

$\mathrm{w_p}$ plastic limit

R_p radial position of elastic-plastic boundary (cylindrical cavity)

R_{sp} radial position of elastic-plastic boundary (spherical cavity)