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Soft clay foundation improvement via prefabricated vertical drains and vacuum preloading

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SOFT CLAY FOUNDATION IMPROVEMENT VIA PREFABRICATED VERTICAL DRAINS AND VACUUM PRELOADING

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by

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CERTIFICATION

I, Chamari Inomika Bamunawita, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Department of Civil Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

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Chamari Inomika Bamunawita

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ABSTRACT

This thesis includes the numerical modelling of prefabricated vertical drain (PVD) subjected to vacuum loading in a 2-D plane strain finite element model employing the modified Cam-clay theory, and the experimental evaluation of effectiveness of combined vacuum and surcharge preloading using a large scale, radial drainage consolidometer. The original axisymmetric analysis and plane strain analysis of vertical drains including the effect of smear and well resistance have been well documented in the past for surcharge preloading. In this study, the existing axisymmetric and plane strain theories of a unit cell are modified to incorporate the vacuum pressure application. Unsaturation of drain soil boundary owing to the vacuum pressure is also considered in the numerical modeling. Thereafter, a multi-drain, plane strain analysis is conducted to study the performance of the entire embankment stabilised with vertical drains subjected to vacuum preloading, for two case histories taken from Thailand.

A laboratory technique of evaluating the effectiveness of combined vacuum and surcharge preloading is elaborated. In this approach, a central vertical drain was installed in soil specimens placed in a large stainless steel cell (450 mm in diameter and 950 mm in height) using a specially designed mandrel, and then the vacuum and surcharge loads were applied using the two different loading systems. The results clearly show the effectiveness of vacuum preloading. Following initial laboratory simulation in the large-scale radial drainage consolidometer, a different approach to conventional analysis is adopted to analyse the vacuum assisted consolidation around vertical drains. It is assumed here that a linear variation of negative pore pressure along

the drain length and a constant (maximum) suction head at the ground surface are realistic and sufficient. The observed retardation of pore pressure dissipation is explained through a series of finite element models, which consider the effect of unsaturation at the drain-soil interface. The results indicate that the introduction of an unsaturated soil layer adjacent to a PVD improves the accuracy of numerical predictions.

The knowledge gained from the modeling of large-scale consolidometer cell is applied to study the behaviour of two embankments built on soft clay, stabilised with vertical drains subjected to vacuum loading. A multi-drain analysis is conducted and the field measurements are compared with a series of numerical model predictions. The best predictions of settlement, lateral displacements and pore pressures are obtained when the numerical analysis included the time and depth dependent changes in vacuum pressure, in addition to having an unsaturated layer of elements along the external boundary of the PVD. Finally, a comprehensive multi-drain analysis is used to predict the failure height of embankment, considering various parameters such as embankment geometry, construction method, sub soil properties and soil improvement techniques.

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a	Width of band drain
a_v	Coefficient of compressibility
b	Thickness of band drain
b_s	Equivalent width of smear zone in plane strain
b_w	Equivalent width of drain (well) in plane strain
B	Equivalent half width of the plane strain cell
c_h	Coefficient of horizontal consolidation
c_u	Undrained shear strength
c_v	Coefficient of vertical consolidation
C_c	Compression index
C_f	Ratio of field and laboratory coefficient of permeability
C_k	Permeability change index
C_r	Recompression index
C_α	Secondary compression index
d_e	Equivalent diameter of band drain
d_s	Diameter of smear zone
d_w	Diameter of drain (well)
D	Diameter of effective influence zone of drain
D_{15}	Diameter of clay particles corresponding to 15% passing
D_{50}	Diameter of clay particles corresponding to 50% passing
D_{85}	Diameter of clay particles corresponding to 85% passing
e	Void ratio
e_{cs}	Void ratio on the critical state line for value of $p'=1$
e_o	Initial void ratio
E	Young's modulus
E_u	Young's modulus for undrained shear
F_t	Influence factor of drain due to time
F_c	Influence factor of drain due to drain deformation

F_{fc}	Influence factor of drain due to clogging
G	Shear modulus
G_s	Specific gravity
H_d	The longest drainage path
H_o	Initial thickness of compressible soil
i	Hydraulic gradient
i_o	Initial hydraulic gradient
I_c	Influence factor
I_p	Plasticity index
k	Permeability
k_{ax}	Axisymmetric permeability
k_h	Horizontal coefficient of permeability
k'_h	Horizontal coefficient of permeability in smear zone
k_{hp}	Equivalent horizontal coefficient of permeability in plane strain
k'_{hp}	Equivalent horizontal coefficient of permeability in plane strain
k_v	Vertical coefficient of permeability
k_s	Saturated permeability
k_u	Unsaturated permeability
k_w	Coefficient of permeability of drain
l	Length of drain
L	Well resistance factor
L_L	Liquid limit
m_v	Coefficient of volume change
M	Slope of critical state line
n	Spacing ratio, R/r_w
N	Volume on the normal consolidation line corresponds to $p'=1$
O_{95}	Apparent opening size
O_{15}	Apparent opening size
O_{85}	Apparent opening size
p'	Effective mean normal pressure

p'_c	Isotropic preconsolidation pressure
P	Normal load
PI	Plasticity index
q	Unit load
q_w	Axisymmetric vertical drain discharge capacity
q_{wa}	Axisymmetric discharge capacity
q_{wp}	Plane strain discharge capacity
q_z	Plane strain discharge capacity
Q	Discharge capacity
Q_w	Discharge capacity in plane strain
r	Radius
r_k	Anisotropy ratio
r_m	Radius of mandrel
r_s	Radius of smeared zone
r_w	Radius of vertical drain (well)
R	Radius of axisymmetric unit cell
s	Smear ratio, r_s/r_w
S	Field spacing of drains
S_e	Effective degree of saturation
S_r	Degree of saturation
S_{ru}	Residual water saturation
t	Time
T_h	Time factor for horizontal drainage
T_{hp}	Time factor for horizontal drainage in plane strain
T_v	Time factor for vertical drainage
T_{50}	Time factor for 50% consolidation
T_{90}	Time factor for 90% consolidation
u	Pore water pressure
u_a	Pore air pressure
u_o	Initial pore water pressure
u_r	Excess pore water pressure in radial direction

u_{sur}	Applied surcharge pressure
u_{vac}	Applied vacuum pressure in axisymmetric condition
u_{vacp}	Applied vacuum pressure in plane strain condition
u_w	Pore water pressure
$\overline{U}$	Average degree of consolidation
U_{10}	10 % degree of saturation
U_{ax}	Degree of consolidation in axisymmetric
U_{pl}	Degree of consolidation in plane strain
v	Rate of flow
V	Volume
w	Water content
w_L	Liquid limit
w_P	Plastic limit
z	Depth (thickness) of soil layer
α	Geometric parameter representing smear in plane strain
α	Ratio of maximum lateral displacement to settlement
β	Geometric parameter representing smear in plane strain
β_1	Ratio of maximum lateral displacement to corresponding fill height
β_2	Ratio of maximum settlement to corresponding fill height
χ	Effective stress parameter
ε	Strain
γ_s	Unit weight of soil
γ_w	Unit weight of water
η	Stress ratio
μ	Smear and well resistance factor in axisymmetric
μ_p	Smear and well resistance factor in plane strain
Γ	Volume on the critical state line corresponds to p′=1; $\Gamma=e_{cs}+1$
κ	Slope of swelling line
λ	Slope of consolidation line
ν	Poison’s ratio

θ	Geometric parameter representing well resistance in plane strain
ρ	Settlement
ρ_∞	Settlement at infinity
σ_h	Total horizontal stress
σ_v	Total vertical stress
σ'_h	Effective horizontal stress
σ'_v	Effective vertical stress
σ'_p	Preconsolidation pressure
σ_r	Radial stress
σ_z	Vertical stress at depth z
σ'_{vo}	Effective overburden pressure
σ_θ	Circumferential stress
σ_1	Axial stress
σ_3	Confining stress
τ	Shear stress