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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**

A thesis submitted in fulfilment of the  
requirements for the award of the degree

**Doctor of Philosophy**

from

**University of Wollongong**

by

**Chamari Bamunawita, BSc Eng (Hons)**

Department of Civil Engineering

2004

## **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

23 February 2004

## 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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## LIST OF SYMBOLS

$a$	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
$C_\alpha$	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
$\bar{U}$	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
$\alpha$	Geometric parameter representing smear in plane strain
$\alpha$	Ratio of maximum lateral displacement to settlement
$\beta$	Geometric parameter representing smear in plane strain
$\beta_1$	Ratio of maximum lateral displacement to corresponding fill height
$\beta_2$	Ratio of maximum settlement to corresponding fill height
$\chi$	Effective stress parameter
$\varepsilon$	Strain
$\gamma_s$	Unit weight of soil
$\gamma_w$	Unit weight of water
$\eta$	Stress ratio
$\mu$	Smear and well resistance factor in axisymmetric
$\mu_p$	Smear and well resistance factor in plane strain
$\Gamma$	Volume on the critical state line corresponds to $p'=1$ ; $\Gamma=e_{cs}+1$
$\kappa$	Slope of swelling line
$\lambda$	Slope of consolidation line
$\nu$	Poisson's ratio



$\theta$	Geometric parameter representing well resistance in plane strain
$\rho$	Settlement
$\rho_{\infty}$	Settlement at infinity
$\sigma_h$	Total horizontal stress
$\sigma_v$	Total vertical stress
$\sigma'_h$	Effective horizontal stress
$\sigma'_v$	Effective vertical stress
$\sigma'_p$	Preconsolidation pressure
$\sigma_r$	Radial stress
$\sigma_z$	Vertical stress at depth $z$
$\sigma'_{vo}$	Effective overburden pressure
$\sigma_{\theta}$	Circumferential stress
$\sigma_1$	Axial stress
$\sigma_3$	Confining stress
$\tau$	Shear stress