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Analytical solutions for modeling soft soil consolidation by vertical drains

Rohan Walker
University of Wollongong

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ANALYTICAL SOLUTIONS FOR MODELING SOFT SOIL CONSOLIDATION BY VERTICAL DRAINS

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

Doctor of Philosophy

from

University of Wollongong, NSW Australia

by

Rohan Walker, B. Eng (Hons. I)

School of Civil, Mining and Environmental Engineering

2006

CERTIFICATION

I, Rohan Walker, declare that this thesis, submitted in fulfillment 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.

Rohan Walker

2nd June 2006

ABSTRACT

Vertical drains increase the rate of soil consolidation by providing a short horizontal drainage path for pore water flow, and are used worldwide in many soft soil improvement projects. This thesis develops three new contributions to the solution of consolidation problems: (i) a more realistic representation of the smear zone where soil properties vary gradually with radial distance from the vertical drain; (ii) a nonlinear radial consolidation model incorporating void ratio dependant soil properties and non-Darcian flow; and (iii) a solution to multi-layered consolidation problems with vertical and horizontal drainage using the spectral method. Each model is verified against existing analytical solutions and laboratory experiments conducted at the University of Wollongong, NSW Australia. The nonlinear radial consolidation model and the spectral method are verified against two trial embankments involving surcharge and vacuum loading at the Second Bangkok International Airport, Thailand. The versatility of the spectral method model is further demonstrated by analysing ground subsidence associated with ground water pumping in the Saga Plain, Japan.

New expressions for the smear zone μ parameter, based on a linear and parabolic variation of soil properties in the radial direction, give a more realistic representation of the extent of smear and suggest that smear zones may overlap. Overlapping linear smear zones provide some explanation for the phenomena of a minimum drain spacing, below which no increase in the rate of consolidation is achieved. It appears this minimum influence radius is 0.6 times the size of the linear smear zone. The new smear zone parameters may be used with consolidation models (ii) and (iii), as mentioned above.

The analytical solution to nonlinear radial consolidation is valid for both Darcian and non-Darcian flow and can capture the behaviour of both overconsolidated and normally consolidated soils. For nonlinear material properties, consolidation may be faster or slower when compared to the cases with constant material properties. The difference depends on the compressibility/permeability ratios (C_v/C_k and C_r/C_k), the preconsolidation pressure and the stress increase. If $C_v/C_k < 1$ or $C_r/C_k < 1$ then the coefficient of consolidation increases as excess pore pressures dissipate and consolidation is faster.

The multi-layered consolidation model includes both vertical and radial drainage where permeability, compressibility and vertical drain parameters vary linearly with depth. The ability to include surcharge and vacuum loads that vary with depth and time allows for a large variety of consolidation problems to be analysed. The powerful model can also predict consolidation behaviour before and after vertical drains are installed and has potential for nonlinear consolidation analysis.

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PUBLISHED WORK

The following publications are related to this PhD thesis:

Walker, R. and Indraratna, B. (2006). “Vertical drain consolidation with parabolic distribution of permeability in smear zone”. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, in press July, 2006.

In preparation:

Walker, R. and Indraratna, B. “Vertical drain consolidation with non-Darcian flow and void ratio dependent compressibility and permeability”.

Walker, R. and Indraratna, B. “Consolidation of stratified soil with vertical and horizontal drainage under surcharge and vacuum loading”.

Walker, R. and Indraratna, B. “Vertical drain consolidation with overlapping smear zones”.

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LIST OF SYMBOLS

| | |
|------------------|--|
| a | PVD width |
| \mathbf{A} | vector of time dependant coefficients |
| A | smear zone permeability parameter; function; time dependant coefficient; cyclic load amplitude |
| A_η | smear zone compressibility parameter |
| b | PVD thickness |
| B | smear zone permeability parameter |
| B_η | smear zone compressibility parameter |
| C | smear zone permeability parameter; integration constant |
| \mathbf{c} | vector of constants |
| \tilde{c}_h | horizontal coefficient of consolidation for non-Darcian flow |
| \tilde{c}_{h0} | initial horizontal coefficient of consolidation for non-Darcian flow |
| C_c | compression index |
| c_h | horizontal coefficient of consolidation |
| c_{h0} | initial value of horizontal consolidation coefficient |
| c_{h1}, c_{h2} | horizontal consolidation coefficients for double layered ground |
| c_{he} | effective consolidation coefficient |
| c_{hf} | final value of horizontal consolidation coefficient |
| C_k | permeability change index |
| C_r | recompression index |
| CS | function |
| c_v | vertical coefficient of consolidation |
| \bar{c}_v | reference value of vertical consolidation coefficient |
| c_{v1}, c_{v2} | vertical consolidation coefficients for double layered ground |
| D_{85} | diameter of clay particles corresponding to 85% passing |
| d_e | diameter of influence area |
| dQ_1, dQ_2 | infinitesimal volume flows |
| dT_h | reference horizontal time factor divided by time |
| dT_v | reference vertical time factor divided by time |
| d_w | drain diameter |
| e | void ratio |
| \mathbf{E} | matrix of eigenvalue exponential terms |
| e_0 | initial void ratio |
| e_{00} | initial void ratio at soil surface |
| e_{0n} | void ratio at the depth below which soil is normally consolidated |
| e_f | final void ratio |
| e_r | error |

| | |
|--------------------------|---|
| F | function |
| f | source/sink term; function; cyclic load natural frequency |
| F_c | discharge capacity reduction factor due to bending |
| F_{fc} | discharge capacity reduction factor due to filtration and clogging |
| F_t | discharge capacity reduction factor due to lateral pressure |
| g | function |
| G_s | specific weight of soil solids |
| H | height of soil; drainage length |
| H_0 | initial height of soil |
| H_1, H_2 | layer depths for double layered ground |
| h_c | height of clay layer |
| h_s | height of sand layer |
| i | hydraulic gradient; integer |
| i_l | critical hydraulic gradient for non-Darcian flow |
| j | integer |
| J_0, Y_0 | bessel functions |
| \bar{k} | reference value of permeability |
| \tilde{k} | non-Darcian coefficient of consolidation |
| \tilde{k}_h | undisturbed non-Darcian horizontal permeability |
| \tilde{k}_s | smear zone non-Darcian horizontal permeability |
| k_0 | permeability at soil/drain interface; initial coefficient of permeability |
| k_1 | ratio of vacuum pressure at drain bottom to drain top |
| k_{clay} | clay permeability |
| k_{filter} | PVD filter permeability |
| k_h | undisturbed horizontal coefficient of permeability |
| \bar{k}_h | reference value of horizontal permeability |
| k_{h1}, k_{h2} | horizontal permeability for double layered ground |
| k_s | smear zone permeability |
| k_{sand} | sand permeability |
| k_{soil} | soil permeability |
| $k_{\text{undisturbed}}$ | coefficient of permeability for undisturbed soil |
| k_v | vertical coefficient of permeability |
| \bar{k}_v | reference value of vertical permeability |
| k_{v1}, k_{v2} | vertical permeability for double layered ground |
| k_{vB} | vertical permeability at bottom of soil layer |
| K_{ve} | equivalent vertical coefficient of permeability |
| k_{vT} | vertical permeability at top of soil layer |
| k_w | drain permeability |
| l | depth of vertical drain; integer |

| | |
|---------------------------|---|
| L | linear operator |
| $\#l$ | number of soil layers |
| m | integer; overconsolidated shear strength index |
| M | summation term e.g. $M = (2m + 1)\pi/2$ in Terzaghi theory |
| M^- | function |
| M^+ | function |
| m_v | coefficient of volume compressibility |
| \bar{m}_v | reference value of volume compressibility |
| m_{v0} | initial value of volume compressibility; volume compressibility at soil/drain interface |
| m_{va} | average value of volume compressibility |
| m_{vB} | volume compressibility at bottom of soil layer |
| m_{vS} | smear zone volume compressibility |
| m_{vT} | volume compressibility at top of soil layer |
| m_{vX} | volume compressibility where interacting smear zones begin to overlap |
| n | ratio of influence radius to drain radius; non-Darcian flow index |
| N | ratio of influence radius to drain radius; integer |
| n' | ratio of influence radius to equivalent mandrel radius based on the mandrel perimeter |
| O_{95} | 95% of filter openings are smaller than this opening |
| OCR | overconsolidation ratio |
| P | cyclic load wave period |
| p_0 | vacuum pressure at soil surface |
| P_{av} | averaging factor to account for changing coefficient of consolidation |
| PTIB | pervious top impervious bottom boundary condition |
| PTPB | pervious top pervious bottom boundary condition |
| q_w | drain discharge capacity |
| $q_{w(\text{required})}$ | required discharge capacity |
| $q_{w(\text{specified})}$ | discharge capacity specified to manufacture |
| r | radial coordinate |
| r_e | radius of influence area |
| r_m | equivalent radius of mandrel |
| r_s | radius of smear zone |
| s | integration variable |
| \bar{s} | mean square distance of the flownet draining a circular area to a rectangular drain. |
| s_{constant} | smear zone size calculated with constant permeability smear zone |
| $s_{\text{equivalent}}$ | smear zone size calculated with linear or parabolic permeability producing equivalent consolidation to smear zone calculated with constant permeability |
| SN | function |
| S_p | drain spacing interval |

| | |
|---------------------|---|
| S_u | undrained shear strength |
| s_X | ratio of smear zone interaction radius to drain radius |
| t | time |
| \tilde{T} | modified time factor |
| \tilde{T}_{Darcy} | Darcian time factor |
| \tilde{T}_m | modified time factor at application of m^{th} instantaneous load |
| \tilde{T}_p | modified time factor at preconsolidation pressure |
| t_{90} | time required to reach 90% consolidation |
| T_c | construction time factor |
| t_f | end time for integration |
| T_h | time factor for horizontal consolidation |
| T_{h0} | horizontal time factor calculated from initial parameters |
| t_{Ω} | drain installation time; piecewise nonlinear time marker |
| t_s | starting time for integration |
| T_v | time factor for vertical consolidation |
| U | degree of consolidation |
| u | pore water pressure |
| \bar{u} | average excess pore pressure |
| $\bar{\bar{u}}$ | depth averaged pore pressure |
| \bar{u}_0 | initial excess pore pressure |
| $\Delta\bar{u}$ | change in pore pressure |
| \bar{u}_{δ} | fundamental pore pressure solution |
| U_h | average degree of consolidation in the horizontal direction |
| U_{hs} | degree of consolidation calculated with settlement data |
| u_m^- | pore pressure immediately before application of m^{th} instantaneous load |
| u_m^+ | pore pressure immediately after application of m^{th} instantaneous load |
| u_s | smear zone pore pressure |
| U_z | average degree of consolidation in the vertical direction |
| \mathbf{v} | matrix of eigenvectors |
| w | pore pressure in the drain; vacuum pressure |
| W | normalised pore pressure |
| \mathbf{w} | matrix dependant on vacuum loading terms |
| W_p | normalised pore pressure at preconsolidation pressure |
| \mathbf{x} | vector of unknown coefficients |
| x | integration variable |
| y | transformed integration variable |
| z | depth coordinate |
| Z | normalised depth |
| z_n | depth below which all soil is normally consolidated |

Greek symbols

| | |
|----------------------------------|---|
| α | non-Darcian radial consolidation parameter; function parameter; soil property parameter |
| λ | non-Darcian radial consolidation parameter; slope of Cam-clay consolidation line; spectral method eigenvalue |
| β | non-Darcian radial consolidation parameter; slope of Asaoka plot; function variable |
| χ | vector of constants |
| $\#\chi$ | number of series term used in previous time step |
| Δ | change operator |
| δ | dirac delta function |
| ε | strain |
| $\partial\varepsilon/\partial t$ | volumetric strain rate |
| η | lumped vertical drain parameter; ratio of undisturbed volume compressibility to drain/soil interface volume compressibility |
| $\bar{\eta}$ | reference value of lumped drain parameter |
| η_X | ratio of interacting smear zone volume compressibility to drain/soil interface compressibility |
| Γ | matrix dependant on compressibility and geometry parameters |
| γ_w | unit weight of water |
| κ | ratio of undisturbed permeability to permeability at the drain/soil interface; slope of Cam-clay swelling line |
| κ_X | ratio of interacting smear zone permeability to drain/soil interface permeability |
| Λ | function |
| μ | smear zone parameter for Darcian flow |
| μ^* | composite smear zone parameter |
| μ_{m_v} | smear zone compressibility parameter |
| μ_w | well resistance parameter |
| μ_X | overlapping smear zone parameter |
| Ω | matrix dependant on non-zero initial condition |
| ω | cyclic load angular frequency |
| ϕ | basis function |
| Φ | vector of basis functions |
| $\bar{\phi}$ | integrated basis function |
| $\bar{\Phi}$ | vector of integrated basis functions |
| φ | cyclic load phase |
| Ψ | matrix dependant on permeability, and geometry parameters |
| ρ | settlement |
| ρ_c | consolidation or primary settlement |
| ρ_i | immediate or distortion settlement |
| ρ_∞ | final settlement |
| ρ_l | settlement caused by lateral displacement |
| ρ_s | secondary compression |
| ρ_t | total settlement |

| | |
|------------------|---|
| σ | total stress |
| σ | matrix dependant on surcharge loading terms |
| $\bar{\sigma}$ | average total stress |
| $\bar{\sigma}'$ | average effective stress |
| σ' | effective stress |
| σ'_0 | initial effective stress |
| σ'_{00} | initial effective stress at soil surface |
| σ'_{0n} | this effective stress marks the depth below which soil is normally consolidated |
| σ'_{0z} | initial effective stress at depth z |
| σ'_{\max} | evolving maximum effective stress |
| σ'_p | preconsolidation stress |
| σ'_{v0} | vertical effective stress |
| $\Delta\sigma$ | change in total stress |
| τ | time |
| θ | function parameter |
| Θ | matrix dependant on cyclic loading terms |
| v | velocity of flow |
| v_r | velocity of flow in radial direction |
| v_v | velocity of flow in the vertical direction |
| Ξ | function |
| ζ | depth |
