

LOAD-SETTLEMENT BEHAVIOUR OF GRANULAR PILES

by

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SYNOPSIS

In this thesis an examination is made of the vibro-replacement technique for the stabilisation of cohesive soils. Improvement is achieved by the formation of stiffer columns of granular material within the soil deposit using a large cylindrical vibrator referred to as a vibroflot. Granular piles (also termed stone columns) are used either singly or in small groups to support isolated footings or large numbers are installed in a regular array to support widespread loads. Each of these modes of application are investigated. For convenience, the work may be divided broadly into four sections.

(a) Presentation of a finite element method for analysing a single granular pile in which slip at the pile-soil interface is taken into account. Both the pile and soil are treated as ideal elasto-plastic materials. The soil is taken to be purely cohesive while the pile is treated as a purely frictional dilatant material which does not necessarily obey an associated flow law. A finite element method suitable for the analysis of single conventional piles is also described.

(b) The finite element analysis is used to investigate the load-settlement behaviour of a single granular pile. The theoretical results indicate the general effects of the pile and soil properties on the load-settlement behaviour of the piles. The analysis is then used to reproduce the results of a field load test. Settlement influence factors for single piles, produced from an elastic analysis, are presented. These influence factors are used in conjunction with interaction factors, derived from the same ana-

lysis, to estimate the settlement of small groups of granular piles.

(c) Attention is then focussed on the use of large numbers of granular piles installed in a regular array to stabilise an extensive area. Except near the edges of the loaded area, the behaviour of all pile-soil units is virtually the same, and consequently only one pile-soil unit need be analysed. Improvement of the soil behaviour is due to (i) the presence of the stiffer pile, (ii) the sand-drain action of the pile which promotes more rapid consolidation of the clay. The results of elastic finite element analyses are presented which quantify the reduction in settlement under drained conditions of soft clays reinforced with granular piles and subjected to a uniform pressure applied over a large area. A series of diffusion theory solutions have been obtained for a parametric study of the increased rate of consolidation of the clay due to the installation of the piles. An analytic solution is then presented for the settlement of a rigid raft supported by the reinforced clay. Finite element solutions to Biot's equations are presented for the rate of settlement of the rigid raft. Expressions are also given for the bending moment and shear force distributions in the raft.

(d) Finally, the results of a limited laboratory programme, designed to verify the applicability of the finite element analysis and elastic settlement theory, are presented.

PREFACE

The candidate carried out the work described in this thesis during the period 1973-1978. All the work was conducted in the School of Civil Engineering, The University of Sydney. The candidate was supervised by Dr. H.G. Poulos, Reader in Civil Engineering, except for a period during 1976 when he was supervised by Dr. P.T. Brown.

The By-Laws of the University of Sydney require a candidate for the degree of Doctor of Philosophy to indicate which sections of the thesis are original. Any information or ideas derived from the many references used during this research programme have been acknowledged in the text. In accordance with the abovementioned By-Laws the Author claims originality for the following work:

(i) In Chapter 3 the method of separating the pile and soil bodies to overcome the necessity of using special joint elements is claimed as original, although analyses following a similar basic procedure have been presented previously.

(ii) In Chapter 3 the method of incorporating dual nodes at the pile-soil interface for the analysis of slip are claimed as original. The treatment of frictional-dilatant slip and in particular the transformations of the governing equations so that the same solution procedure used for the analysis of an adhesive interface can be retained, is claimed as original. In addition, the technique of reducing the size of the equation set for elasto-plastic finite element analyses is claimed as original.

(iii) In Chapter 4 the application of the finite element analysis, in which a pile-soil interface strength can be specified, for predicting the results from field load tests is claimed as original.

(iv) In Chapter 5 all numerical results for the reduction in settlement under drained conditions of soft clays reinforced with granular piles and subjected to a uniform pressure are claimed as original.

(v) In Chapter 6 all numerical results showing the increased rate of consolidation of the clay due to the installation of the piles are claimed as original.

(vi) In Chapter 7 the analytic solution for the settlement of a rigid raft, seated on clay stabilised by granular piles, is claimed as original.

A number of papers were prepared and published by the author and others during the period of the author's candidature. These are submitted in support of his candidature. They are:

1. BALAAM, N.P., POULOS, H.G. and BOOKER, J.R. (1975), "Finite Element Analysis of the Effects of Installation on Pile Load-Settlement Behaviour", Geotechnical Engineering, Vol. VI, No. 1, pp. 33-48.
2. BALAAM, N.P., BOOKER, J.R. and POULOS, H.G. (1976), "Analysis of Granular Pile Behaviour using Finite Elements", Proc. Int. Conf. on Finite Element Methods in Eng., Adelaide, pp. 29. 1-13, 1976.

3. ROWE, R.K., BOOKER, J.R. and BALAAM, N.P. (1976), "Application of the Initial Stress Method to Soil Structure Interaction", accepted for publication, Int. J. Num. Meth. in Engng., see also Res. Report No. 294, School of Civil Engineering, University of Sydney.
  
4. BALAAM, N.P., POULOS, H.G. and BROWN, P.T. (1977), "Settlement Analysis of Soft Clays Reinforced with Granular Piles", Proc. 5th S.E. Asian Conf. on Soil Engineering, Bangkok, pp. 81-92.

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N.P.B.

NOTATION

All notation and symbols are defined where they first appear in the text. For convenience, the more frequently used symbols and their meanings are listed below.

$A_p$	Cross-sectional area of pile
$a$	Radius of footing, radius of pile
$b$	Footing width, radius of equivalent circular domain of influence of pile
$c_a$	Adhesion at pile-soil interface
$c_u$	Undrained cohesion
$c'$	Cohesion of soil skeleton
$c_{r1}$	Coefficient of consolidation in the radial direction for one dimensional strain conditions
$c_{v1}$	Coefficient of consolidation in the vertical direction for one dimensional strain conditions
$c_{v3}$	Coefficient of consolidation in the vertical direction for three dimensional strain conditions
$[D_E]$	Elasticity matrix
$d$	Pile diameter
$d_e$	Effective diameter of a pile's domain of influence
$E_p', E_p, E_1$	Young's modulus of pile
$E_s$	Undrained Young's modulus of soil
$E_s', E_2$	Young's modulus of soil skeleton
$E_s(0)$	Young's modulus of soil at surface
$E_s(h)$	Young's modulus of soil at depth $h$
$\{F\}$	Force vector

$G$	Shear modulus
$G_o$	Shear modulus at surface
$h$	Depth of soil layer
$I_D$	Displacement influence factor
$K$	Relative stiffness of pile and soil
$[K_E]$	Elastic stiffness matrix
$[K_{EP}]$	Plastic stiffness matrix
$k_h$	Permeability in the horizontal direction
$k_v$	Permeability in the vertical direction
$L$	Length of pile
$M_1$	Major principal moment
$M_2$	Minor principal moment
$M_r$	Moment in the radial direction
$M_t$	Moment in the tangential direction
$m_{v1}$	Coefficient of volume change for piles
$m_{v2}$	Coefficient of volume change for soil
$P$	Applied load
$p$	Magnitude of applied traction
$P_1$	Reaction stress in pile minus the applied traction
$Q$	Shear force
$q, q_A$	Magnitude of applied traction
$R_s$	Sum of interaction factors for group settlement
$r$	Radial co-ordinate
$r_e$	Effective radius of a pile's domain of influence
$r_w$	Radius of pile
$s$	Pile spacing
$T_h$	Time factor defined in terms of $c_{r1}$
$T_{v1}$	Time factor defined in terms of $c_{v1}$
$t$	Time

$t_{50}$	Time for 50% consolidation
$U_o$	Pore water pressure
$U_p$	Degree of pore pressure dissipation
$U_R$	Degree of pore pressure dissipation for radial flow
$U_s$	Degree of settlement
$u$	Excess pore pressure
$u_o$	Initial excess pore pressure
$u_r$	Radial displacement
$u_t$	Excess pore pressure at time $t$
$x, y, z$	Cartesian co-ordinates
$Z$	Cartesian co-ordinate
$\alpha_f$	Interaction factors computed from an elastic analysis of two identical piles
$\gamma_t, \gamma$	Bulk density
$\gamma_w$	Density of water
$\Delta$	Footing displacement, finite increment
$\delta_{\text{elastic}}$	Footing displacement for elastic continuum
$\delta$	Footing displacement
$\partial$	Differential operator
$\epsilon_z$	Vertical strain
$\epsilon_v$	Volume strain
$\theta$	Bulk stress, angular measure
$\nu$	Poisson's ratio
$\nu_p', \nu_p, \nu_1$	Poisson's ratio of pile
$\nu_s', \nu_2$	Poisson's ratio of soil skeleton
$\nu_{\text{RAFT}}$	Poisson's ratio of raft
$\sigma_1, \sigma_2, \sigma_3$	Principal stresses
$\sigma_h$	Horizontal stress
$\sigma_R$	Radial stress

$\sigma_{\theta}$	Circumferential stress
$\sigma_z$	Vertical stress
$\phi, \phi'$	Angle of internal friction
$\phi_a$	Angle of friction for interface slip
$\psi$	Angle of dilatancy of pile material
$\psi_a$	Angle of dilatancy of interface