# PRACTICAL SOIL DYNAMICS

GEOTECHNICAL, GEOLOGICAL AND EARTHQUAKE ENGINEERING

Volume 20



For further volumes:
http://www.springer.com/series/6011

# Practical Soil Dynamics

## Case Studies in Earthquake and Geotechnical Engineering

*by*

MILUTIN SRBULOV
*United Kingdom*

Springer

Dr. Milutin Srbulov
United Kingdom
srbulov@aol.com

ISSN 1573-6059
ISBN 978-94-007-1311-6 e-ISBN 978-94-007-1312-3
DOI 10.1007/978-94-007-1312-3
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2011928823



Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

# Preface

Karl Terzaghi formally defined soil mechanics as a separate discipline by publishing his first book in 1925. Although soil mechanics involves soil statics and dynamics, only soil statics has become well established while soil dynamics remained in a rudimentary stage until recent developments in the field of earthquake engineering. Geotechnical earthquake engineering is formally defined as a new discipline by the first international conference on geotechnical earthquake engineering held in Tokyo in 1995. An essential part of geotechnical earthquake engineering is soil dynamics.

Engineering codes and standards have followed to some extent developments in research in ground vibrations and earthquake engineering. Recent EN 1998-5 (2004) provides norms and information on a limited range of subjects only such as topographic amplification factors, liquefaction of levelled ground but not slopes, loading on retaining walls but not reinforced soil and seismic bearing capacity of shallow foundations but not piled foundations and not on soil-structure interaction. Such limitations are understandable as codes and standards are based on best practice and when a consensus on best practice is absent then codes remain brief. However, engineering practice require acceptable solutions for many subjects not covered by the existing codes. ISO 23469 (2005) use similar approach to EN 1998-5 (2004).

This volume provides information on the basic mechanisms and factors affecting the behaviour of ground and buried structures in cyclic conditions in order to help engineering judgement. The analyses are based on well known engineering principles and methods that are familiar to many readers. The accuracy and precision of the simple analyses are demonstrated for actual case histories instead of using numerical analyses and laboratory testing, which have their disadvantages such as complexity, high cost and long duration. The equations provided in this volume are suitable for hand calculations.

United Kingdom M. Srbulov

## References

EN 1998-5 (2004) Eurocode 8 – design of structures for earthquake resistance, part 5: foundations, retaining structures and geotechnical aspects. European Committee for Standardization, Brussels

ISO 23469 (2005) Bases for design of structures – seismic actions for designing geotechnical works. International Organization for Standardization

Terzaghi K (1925) Erdbaumechanik auf bodenphysikalisher grundlage. Deuticke, Vienna, Austria

# Acknowledgements

I was honoured and privileged to work with Professor Nicholas Ambraseys as his assistant (i.e. associate after the completion of my PhD in 1994) on a number of research projects supported by the Engineering and Physical Science Research Council of the United Kingdom and by the EPOCH program of the Community of European Countries at Imperial College in London (UK) during the period 1991–1997. The simplified approach used in our research is directly applicable to routine engineering practice. My initial involvement with earthquake engineering was a starting point for further work concerning soil dynamics and ground vibration related issues while working on a number of projects worldwide for Mott MacDonald Ltd.

Dr E.T.R. Dean of Caribbean Geotechnical Design Limited (Trinidad) and Soil Models Limited (UK) reviewed several of my papers and was of great help with his detailed and precise comments for the improvement of initial versions of the papers. He kindly reviewed the initial version of this volume and made a significant contribution towards the improvement of the clarity and readability of the text.

Several of my former colleagues influenced my professional carrier and hence this volume. Professor Milan Maksimovic persuaded me to switch profession from concrete structures to geotechnics right after my graduation. He pioneered studies of soil mechanics paid by Energoprojekt Co. at Imperial College in the U.K. The MSc soil mechanics study in 1984/85 enabled me to obtain the position of a research assistant later. Professor Petar Anagnosti (former principal geotechnical engineer of Energoprojekt Co. and former vice president of the International Society for Soil Mechanics and Foundation Engineering) and Mr Aleksandar Bozovic (former technical director of Energoprojekt Co. and former chairman of the committee on seismic aspects of dam design of the International Commission of Large Dams) encouraged me to apply for the position of a research assistant at Imperial College.

The editor of European Earthquake Engineering and Ingegneria Sismica journals Professor Duilio Benedetti accepted kindly for publication 20 of my papers related to geotechnical earthquake engineering in the period 1995 to end of 2010. Numerous publications of my papers encourage me to work more in the field of geotechnical earthquake engineering and related topics such as ground vibration. Dr. Massimo Tognetti from Patron Editore provided publisher's consent to use material from my papers published in the journals European Earthquake Engineering and Ingegneria Sismica.

Ms Petra D. van Steenbergen – a senior publishing editor for geosciences with the publisher Springer showed interest in my proposals for writing books and arranged for the awards of the contracts with the help from Ms Cynthia deJonge.

The idea for writing books came from my wife Radmila, who had no time to do it herself but, instead, provided encouragement and stimulation.

# Contents

# List of Symbols

| Symbol | Description |
|---|---|
| $\varphi$ | equivalent friction angle at the base of a sliding block |
| $\bar{\alpha}$ | inclination to the horizontal of an equivalent block, angle along tunnel circumference |
| $(N_1)_{60}$ | normalized blow count from the standard penetration tests |
| $\ddot{\theta}, \dot{\theta}$ | rotational acceleration, velocity |
| $\ddot{u}, \dot{u}$ | ground horizontal acceleration, velocity |
| $A_{(o)}$ | cross section area, (o) coefficient |
| $a_{(p)h(top),g}$ | horizontal acceleration, (p) peak, (top) at the ground surface, (g) ground |
| $A_f$ | foundation area |
| $A_{fault}$ | fault rupture area |
| $a_{peak,surface,depth}$ | peak horizontal ground acceleration at ground surface/depth in the free field |
| $A_{pilecap}$ | area of pile cap for a pile group or twice the cross section area of a single pile |
| $A_r$ | nominal amplitude of a vibrating roller |
| $a_{structure}$ | structural acceleration |
| $b$ | translational slide toe length, coefficient |
| $B(')$ | structural height above its foundation, foundation width (‘) effective |
| $B_f$ | diameter of an equivalent circular foundation |
| $b_{q,\gamma,c}$ | foundation base inclination factors |
| $b_s$ | width of a vertical slice into which a potential sliding mass is divided |
| $c(')$ | a correction coefficient, coefficient of viscous damping, (‘) soil cohesion in terms of effective stresses (total-pore water pressure) |
| $c_o$ | coefficient of an embedded foundation |
| $c_t$ | coefficient |
| $c_u$ | shear strength of fine grained soil (clayey) including rate effect in undrained condition |

| | |
|---|---|
| $C_\theta$ | dynamic stiffness coefficient in rotation |
| $D$ | diameter of the middle of a tunnel lining, average diameter of a circular cylinder |
| $d_{(h)}$ | horizontal distance between forces or places, minimal distance from location of interest to the surface projection of a fault (or epicentral distance where the location of a causative fault has not been reported), pile diameter, wall embedment depth |
| $D_{50}$ | an average diameter of soil particles |
| $D_b$ | distance to blast location |
| $d_f$ | earthquake source to observation site distance |
| $D_f$ | foundation depth |
| $d_g$ | design ground displacement |
| $D_p$ | external pile diameter |
| $d_p$ | pile wall thickness for hollow piles |
| $d_{p,h}$ | peak horizontal ground displacement |
| $d_{q,\gamma,c}$ | foundation depth factors |
| $D_r$ | soil relative density |
| $D_s$ | maximum surface displacement of a tectonic fault, depth of a vibration source |
| $e$ | soil void ratio, eccentricity of mass centre of gravity with respect to a pile cap underside level, embedment depth of a cylinder, eccentricity of the resultant force on footing area |
| $E_{(p)}$ | Young's modulus, (p) pile |
| $E_{(s)a,(s)p}$ | lateral (s) static active (a) and passive (p) force on a wall |
| $E_{ff}$ | theoretical free-fall energy of a hammer |
| $EJ$ | flexural stiffness |
| $E_m$ | actual energy delivered by hammer |
| $f$ | frequency of ground motion |
| $F_{(o,f)}$ | factor of safety against sliding of translational landslide, (o) initial, (f) final |
| $F_1$ | resultant horizontal acting force over pile cap area due to kinematic interaction |
| $F_{N,R(T),O}$ | (N) normal and strike-slip, (R) reverse (T thrust), (O) unspecified faulting type indicator |
| $F_{p(np),d,r,s,b}$ | various factor of safety for a wall |
| $F_s$ | factor of safety against soil failure |
| $g$ | gravitational acceleration |
| $G_{max}$ | average equivalent (or maximum) ground shear modulus |
| $g_{q,\gamma,c}$ | ground surface inclination factors |
| $G_s$ | specific gravity of soil solids, equivalent linear soil shear modulus |
| $H$ | height drop of centre of displaced soil mass, soil layer thickness, rectangular tunnel wall height |

| | |
|---|---|
| $h$ | thickness of a translational slide, retained depth of soil behind a wall, depth of water in front of a wall, height of the centre of a mass, soil depth |
| $H_d$ | drop height of a mass |
| $h_f$ | hypocentral depth |
| $H_l$ | distance from a foundation level to the level of soft layer below |
| $h_w$ | wall height |
| $I_o$ | polar moment of mass inertia around the centroid, (o) with respect to its base |
| $i_{q,\gamma,c}$ | factors for foundation load inclination |
| $I_\theta$ | mass moment of inertia of structure with respect to the top of a foundation |
| $J$ | second moment of cross sectional area |
| $j$ | depth of water level below the ground surface behind a wall |
| $k$ | coefficient of material damping, ratio between horizontal and vertical overburden stress |
| $K$ | static stiffness coefficient, constant |
| $K_{(s)a,(s)p,o}$ | coefficient of static (s), active (a), passive (p), at rest (o) lateral soil pressure |
| $k_c$ | ratio between the critical horizontal acceleration at which the factor of safety against soil failure is 1 and the gravitational acceleration |
| $k_p$ | ratio between the peak horizontal ground acceleration and the gravitational acceleration |
| $k_s$ | structural stiffness in horizontal direction |
| $K_s$ | coefficient of punching shear, of lateral effective stress acting on pile shaft |
| $k_{y,x}$ | ratios between the vertical and horizontal inertial and the gravitational acceleration, |
| $k_\theta$ | stiffness coefficient in rocking |
| $K_\theta$ | static stiffness coefficient in rotation |
| $L$ | flow path length of the centre of displaced soil mass, pile depth/length, length of a translational slide |
| $L_f$ | length of a tectonic fault area |
| $l_k$ | critical length for buckling |
| $L_p$ | pile shaft length |
| $L_{p(n,1,2),a(1,2,3)}$ | lever arm of a lateral force (p) passive, (n) net, (a) active side |
| $m$ | mass |
| $M_1$ | bending moment at pile top due to horizontal displacement $\Delta$ |
| $M_2$ | bending moments at pile tops due to inertial effects |
| $m_b$ | body wave magnitude of an earthquake |
| $M_d$ | tamper mass |
| $M_L$ | local (Richter) earthquake magnitude |
| $M_o$ | seismic moment |

| | |
|---|---|
| $m_s$ | mass (s) of a structure |
| $M_s$ | surface wave magnitude of an earthquake |
| $M_w$ | moment magnitude of an earthquake |
| $M_{\Delta,\theta}$ | bending moment at the top of wall/column of a rectangular tunnel due to differential horizontal ground drift $\Delta$ and wall/column rotation $\theta$ |
| $M_\alpha$ | bending moment in a tunnel lining in perpendicular direction to the tunnel axis |
| $M_\omega$ | resultant overturning moment, base reaction moment |
| $n$ | soil porosity |
| $N(')$ | axial force on a sliding surface, (') submerged |
| $n_d$ | number of standard deviations |
| $N_{eqv}$ | equivalent number of uniform stress cycles |
| $N_k$ | cone penetration test factor |
| $n_m$ | vibration mode number |
| $N_{piles}$ | number of piles |
| $N_q$ | pile end bearing coefficient |
| $N_{q,\gamma,c}$ | bearing capacity factor of a shallow foundation |
| $N_{SPT}$ | standard penetration test blow count |
| $OCR$ | over consolidation ratio |
| $p_{(o)}$ | number of standard deviations, (o) |
| $p/\gamma$ | so called pressure height of fluid |
| $p'_{(o)}$ | effective overburden stress |
| $P_1$ | horizontal interaction force between soil and foundation, axial force on the interface between two sliding blocks |
| $p_a$ | atmospheric pressure |
| $P_{critical}$ | critical force to cause buckling of a strut |
| $P_f$ | maximum force amplitude |
| $PI$ | soil plasticity index |
| $p_s$ | line vertical load acting on a vertical slice |
| $P_{w,n,p,a}$ | axial force in pile from static and inertial load, axial force acting on the interface, imbalanced water lateral force, lateral force on a wall (n) net, (p) passive, (a) active |
| $P_\alpha$ | axial force in a tunnel lining in perpendicular direction to the tunnel axis |
| $q_{(f)}$ | surcharge at foundation level, (f) ultimate bearing stress |
| $R$ | resistance force caused by turbulence (collision of particles) and viscosity (rate effects), vertical component of the resultant force at wall base, radius of a circular slip surface, average radius of a circular cylinder/tunnel |
| $r_{(o)}$ | radius of embedded (equivalent) cylinder, vertical shaft radius |
| $R_1$ | resistance force of a pile group with at least two piles in direction of $\Delta$ |
| $r_d$ | stress reduction factor with depth |

| | |
|---|---|
| $r_f$ | minimum horizontal distance at which Reyleigh waves appear at the surface from body waves |
| $R_{x,y}$ | resultants of horizontal and vertical forces respectively acting on a vertical slice |
| $S$ | axial pile stiffness, ground type coefficient |
| $S_a$ | horizontal structural acceleration |
| $S_f$ | average slip of a tectonic fault during an earthquake |
| $s_{q,\gamma,c}$ | foundation shape factors |
| $s_{r,t}$ | radial and tangential displacements of a circular cylinder |
| $S_{S,A}$ | soft and stiff soil sites indicators |
| $S_{\omega,\theta}$ | dynamic stiffness coefficient, in horizontal direction – ω, in rotation - θ |
| $t$ | time |
| $T_{(C,D)}$ | shear force on a sliding surface, duration of sliding of a translational landslide, period of horizontal ground vibration, (C,D) periods of structural vibration |
| $T_1$ | transversal force at pile top due to horizontal displacement $\Delta$ |
| $T_2$ | transversal forces at pile tops due to inertial effects |
| $T_e$ | equivalent fundamental period of structural and ground vibration |
| $T_h$ | fundamental period of horizontal ground vibration |
| $T_n$ | Period of vibration of a soil layer |
| $T_r$ | fundamental period of rocking structural and ground vibration |
| $T_s$ | fundamental period of horizontal structural vibration |
| $T_{\Delta,\theta}$ | transversal force at the top of wall/column of a rectangular tunnel due to differential horizontal ground drift $\Delta$ and wall/column rotation $\theta$ |
| $T_\alpha$ | shear force in a tunnel lining in perpendicular direction to the tunnel axis |
| $u_{1,2}$ | slope and toe displacements of a translational slide |
| $u_{b,1,2}$ | amplitude of horizontal displacements, (b) maximum amplitude of base horizontal displacements, (1) in one direction – down slope, (2) in two directions – of a level ground |
| $u_i$ | radial horizontal displacement of a vertical shaft before soil yield |
| $u_{w(s)}$ | pore water pressure at the base of a vertical slice, (s) above steady state water level for a partially submerged slope |
| $v$ | depth below wall top |
| $V$ | vertical force acting at the foundation underside |
| $v^2/(2g)$ | fluid kinetic energy height |
| $V_p$ | velocity of particle sedimentation in water |
| $v_{p,h}$ | peak horizontal ground velocity |
| $v_{t,l,\ avr}$ | wave velocity, (t) transversal, (l) longitudinal, (avr) averaged |
| $W$ | equivalent block weight or of displaced flow mass |
| $w$ | width of a foundation (& structure) |
| $w_d$ | width of a vibrating drum |

| | |
|---|---|
| $W_e$ | mass of explosive |
| $W_f$ | width of a tectonic fault area |
| $W_{s(')}$ | total weight of a vertical slice (above steady state water level), (')submerged weight of part of a vertical slice below steady state water level |
| $W_z$ | saturated weight of part of a vertical slice below steady state water level |
| $x,r$ | horizontal, slant distance |
| $x_i$ | distance from impact |
| $x_r$ | distance along the ground surface from a roller |
| $y_{r,z}$ | liver arms of the horizontal components of external and inertial forces respectively with respect to the centre of a trial circular slip surface with the radius R |
| $z$ | elevation of fluid above a reference datum, height of truncated part of a cone |
| $z_1$ | pile settlement |
| $\Delta E_a$ | dynamic increment of active soil lateral force |
| $\Delta M_\theta$ | second moment of inertia of trapped mass of soil beneath a foundation in rotation when the Poisson's ratio >1/3 |
| $\Delta_s$ | equivalent horizontal displacement of ground surface, (s) differential horizontal soil displacement along tunnel height |
| $\Delta_w \Delta t^{-1}$ | peak particle velocity |
| $\Delta\sigma_{v,z}$ | additional vertical stress at a depth $z$ due to foundation load |
| $H_\omega$ | horizontal harmonic force |
| $\alpha_p$ | ground cohesion mobilization factor along pile shaft |
| $\alpha_{(s)}$ | angle of inclination to the horizontal of an equivalent block and soil cohesion mobilisation factor (s) the base of a vertical slice |
| $\beta$ | angle of rotation of pile cap, angle of inclination to the horizontal of the interface between slip and toe surfaces along slope |
| $\beta_t$ | tuning ratio |
| $\delta_b$ | friction angle between soil and pile cap in coarse grained soil (silt, sand, gravel), angle of inclination to the horizontal of the toe of a slip surfaces along slope, (b) between wall back and soil |
| $\delta_\phi$ | friction angle between ground and pile shaft |
| $\phi_{(1)}$ | soil friction angle, (1) in static condition |
| $\gamma_{s,w}$ | unit weight of soil (s) and water (w) |
| $\gamma_{(d)}$ | (average) shear strain (over pile length), soil unit weight, (d) dry |
| $\eta_{aw}$ | absolute viscosity of water |
| $\eta_w$ | inclination to the horizontal of soil surface at the back of a wall (positive upwards) |
| $\lambda$ | A mean annual rate of exceedance of an earthquake magnitude |
| $\mu$ | shear modulus of the Earth's crust |
| $\nu$ | Poisson's ratio |

| | |
|---|---|
| $o$ | back of wall inclination to the vertical (positive from back to front) |
| $\theta$ | angle of inclination to the horizontal of the slip surfaces along slope, rotation of the structure and its foundation, rotation of a wall/column of rectangular tunnel |
| $\rho$ | ground unit density |
| $\sigma'$ | effective axial stress |
| $\sigma'_m$ | mean principal effective stress |
| $\sigma'_n$ | axial stress acting on the sliding surface along slope |
| $\sigma_3$ | confining effective pressure |
| $\sigma_v(')$ | stress, v –vertical, (‘) – effective, r – radial, t – tangential |
| $\tau_{(hv),max}$ | soil shear strength (hv) in horizontal to vertical plane, (max) maximum |
| $\tau/\sigma'_v$ | stress ratio |
| $\omega_{(d,o)}$ | circular frequency |
| $\xi$ | damping ratio |
| $\psi$ | angle of pile inclination to the vertical, also between horizontal and the gravitational accelerations |