GROUND VIBRATION ENGINEERING

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Ground Vibration Engineering

Simplified Analyses with Case Studies and Examples

by

MILUTIN SRBULOV

United Kingdom

with Foreword of

E.T.R. Dean

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Dr. Milutin Srbulov
United Kingdom
srbulov@aol.com

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Foreword

Ground vibration is a significant geohazard and has always been an important consideration in civil engineering design and construction. Vibrations can be caused naturally, by earthquakes, landslides, wave action, volcanoes, river waterfalls, and other actions (Huang et al., 2007). Vibrations can also be caused by people and technology, such as by road vehicles, trains, shipping, cargo handling, industrial machinery, and war (Sheng et al., 2006). Ground vibration can be caused by very loud noises, including by musical events, and by people marching or dancing. It can be caused by construction plant and operations.

Levels of ground vibration that are strong enough to be felt by people are also strong enough to potentially damage structures and foundations. Damages can include excessive building settlement, liquefaction of sandy soils, slope instability, collapse of trenches, excavations, and tunnels, exposure of buried pipelines and other services, cracking of pipes, and serious discomfort to persons in workplaces, at home, or en route. Conversely, some construction operations deliberately vibrate the soil, such as vibro-coring methods. Other operations have ground vibration as an inevitable consequence, such as pile driving (White et al., 2002).

Ground vibration is also a useful tool in exploration, and can be used to find buried minerals and objects of many kinds. Sometimes things go wrong, however. Jefferies and Been (2006) tell the story of a number of exploration trucks which purposely sent sound waves into the ground, as part of a survey for hydrocarbons. The sound waves liquefied the sandy ground on which the trucks were parked, leading to a slope failure and to the trucks sinking into the quicksand that they had created.

This book brings together the main aspects of the practical knowledge of the art and science of ground vibration engineering. It describes techniques of measuring ground vibration, how to predict the likely maximum ground vibration levels during a structure's design life, how to predict its effects, how to design robust structures and foundations that will withstand design vibration levels, how to design construction operations that use ground vibration effectively when needed, how to minimize it when not, and how to conduct a forensic investigation into ground vibration damage.

Ground vibration is one of the expanding fields within civil engineering, and the practical knowledge and experiences recounted herein will likely help to encourage much needed further research. Some of the topics of current and future work are likely to include development of understanding of cyclic loading effects on soils, development of methods to accurately predict changes of soil stiffness and strength due to cyclic and dynamic loading, further development of safe geophysical methods of ground investigation, increased use of methods of controlled experimentation such as centrifuge modelling (Itoh et al., 2005), and further development of standards, codes of practice, and legislation.

As well as distilling the Author's extensive experience, this book provides extensive reference to and commentaries on technical standards and codes of practice, and references to the key practical and academic references in the technical literature.

Soil Models Limited, Aberdeen, UK E.T.R. Dean
Caribbean Geotechnical Design Limited, Curepe, Trinidad

Preface

Ground vibration consideration is gaining significance with decreasing people's tolerance of vibration, introduction of new environmental legislations, increasing use of equipment sensitive to vibration, ageing of existing buildings and expanding construction sites to/near collapsible/liquefiable/thixotropic soil.

This volume bridges the gap that exists between rather limited provisions of engineering codes/standards and complex numerical analyses/small-scale tests. While a number of the codes/standards and text books are mainly concerned with the effects of vibration on humans and structures very few of them deal with vibration induced ground failures. Numerical analyses, even in elastic domain, require expert knowledge, which is available only within large/specialised companies and at universities.

This volume contains descriptions of ground vibration measurements, predictions and control for engineers. Effects of most frequent sources of ground vibration arising from construction/demolition, traffic and machinery have been considered by simplified analyses aimed at ease and speed of use for major problems in ground vibration engineering. Comments on assumptions, limitations, and factors affecting the results are given. Case studies and examples worldwide are included to illustrate the accuracy and usefulness of simplified methods. A list of references is provided for further considerations, if desired. Microsoft Excel spreadsheets referred to in Appendices and provided on http://extras.springer.com are for the case studies and examples considered in this volume.

Specialists in non-linear dynamics analyses recognize that the motion of a non-linear system can be chaotic and the outcomes can be unrepeatable and unpredictable. The non-linearity arises when stress-strain relationship is non-linear even in elastic strain range and when cracking and plastification occur on yielding of materials at large strain. Baker and Gollub (1992), for example, show that two conditions are sufficient to give rise to the possibility of chaotic motion: the system has at least three independent variables, and the variables are coupled by non-linear relations. Equivalent linear and simplified non-linear dynamic analysis described in this volume can be used to avoid possible chaotic outcomes of complex non-linear dynamic analyses/small-scale tests.

United Kingdom Milutin Srbulov

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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 during the period 1992–1997. 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.

Dr E.T.R. Dean 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.

The editor of European Earthquake Engineering journal Professor Duilio Benedetti accepted kindly for publication eighteen my papers related to geotechnical earthquake engineering in the period 1995 to end of 2007. Numerous publications of my papers encourage me to work more in the field of geotechnical earthquake engineering and related topics such as ground vibration.

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

Contents

List of Symbols

Symbol	Description
$\bar{v}$	an average velocity through an equivalent homogeneous isotropic ground
ϕ_m	phase angle of a Fourier series
∞	symbol for infinity
$u_i, \dot{u}_i, \ddot{u}_i$	horizontal displacement, velocity and acceleration of a SDOFO at time instant *i*
$(N_1)_{60}$	normalized blow count N_{SPT}
$a(t)$, $a[n]$	continuous in time and discrete at time intervals vibration amplitude
A_f	measuring instrument amplitude range, foundation area
A_{loop}	the area of the hysteretic loop
a_m, b_m, c_m	coefficients of *m*th member of a Fourier series
A_r	nominal amplitude of the vibrating roller
$A_{R,T,I}$	amplitudes of reflected (R), transmitted (T) and incident (I) waves
b	width of a slice of a cylindrical trial slip surface
b_c, l_c	breadth and length of a rectangular foundation or a pile cap
B_f	diameter of an equivalent circular foundation
$c(a_o)$	damping coefficient
c, c_o	viscous damping coefficient
c'	effective soil cohesion
$c_{t,p}$	ground wave velocity (t) transversal (p) longitudinal
$c_{u(1)}$	ground cohesion, (1) in one cycle i.e. static condition
$c_{u,avr}$	an average ground cohesion in undrained condition along pile shaft length
D_b	blast distance
d_h	the horizontal distance between the location where the load *V* is acting
d_i	thickness of a ground layer
D_p	external pile diameter
d_p	thickness of wall of a hollow pile
D_r	relative density of soil
dS	surface area
D_s	vibration source depth
$d\tau$	shear stress increment
E	Young modulus, energy
e	void ratio of soil
E_D	dissipated energy
E_{ff}	theoretical free-fall energy
E_{flux}	total energy-flux density per unit time
E_m	actual energy delivered by hammer

Symbol	Description
E_{max}	the maximum strain energy
$E_{o(r)}$	energy at vibration source (o) or at distance (r)
f	frequency of vibration
F	amplitude of a horizontal force acting on a foundation block
$f(t)$	Fourier series
$F_{A,V,D}$	Fourier amplitudes of acceleration (A), velocity (V), displacement (D)
f_c	corner frequency
f_d (f_o)	frequency of an input (output) motion
$F_d(\omega)$, $F[k]$	discrete Fourier transform
f_{max}	cut-off frequency
$F_{R,I}(\omega)$	real and imaginary part of a Fourier transform
F_s	factor of safety of slope stability
$F_{v,b}$	vertical foundation capacity
G	ground shear modulus
G_{max}	the maximum shear modulus
G_s	specific gravity of soil solids
G_{secant}	the secant shear modulus
H	thickness of a homogeneous ground layer
H_b	height of a building
H_d	the drop height
H_f	foundation (structure) height
H_l	distance from foundation level to the level of liquefied layer below
i	imaginary number
I, $I_{m,i}$	mass moment of inertia at a place *i*
I_x	second moment of cross section area at place x
$k(a_o)$	spring coefficient
K_e	static stiffness coefficient
$K_{h,v}$	stiffness of rubber bearings in the horizontal (h)/vertical (v) direction
K_o	the coefficient of soil lateral effective stress at rest
$k_{o,s,x,j}$	stiffness (force per displacement) (o) of an elastic damper, (s) structure, (x) soil, (j) at a place j
K_s	coefficient of lateral effective stress acting on pile shaft, coefficient of punching shear
K_θ	rotational stiffness of a foundation block
L_b	length of a beam
L_f	foundation length
L_p	length of pile in ground
L_s	vibration source length
L_w	wave length
m	mass of a foundation block
m, n, k	counters of a member of Fourier series
M_d	tamper weight
$m_{o,s,x,i}$	mass (o) of a SDOFO, (s) structure, (x) beam (i) at a location
N	even number of member in a fast Fourier transform
n	soil porosity
n_b	analogue to digital converter bit range
N_c	bearing capacity factor
n_d	number of vibration drums
N_i	average blow count of standard penetration test
n_m	vibration mode number

Symbol	Description
N_q	ground bearing capacity factor
N_{SPT}	blow count of standard penetration test (SPT)
N_x	axial force in a beam at place x
OCR	over consolidation ratio
p'_o	effective overburden stress at the foundation depth
P_f	maximum amplitude of vibration force at the ground surface
PI	soil plasticity index
P_Δ	reaction forces at the fixed ends of a beam displaced Δ_P at the end
r	resolution of instrument for ground vibration measurement
$r_{e,v,h,r}$	radius of equivalent disk (v) vertical motion (h) horizontal motion (r) rocking
r_f	radius of near field on the surface
r_o	radius of an equivalent disk
$r_{s,i}$	slant distance
S_e	dynamic stiffness coefficient
$S(\omega)$	power spectral density function
t	time
T_f	time interval of a harmonic function $f(t)$ defined in time t
T_n	period of the nth mode of free vibration of an infinite layer
T_p	period of small amplitude pendulum swaying
T_r	vibration record duration
T_w	wave period
u	horizontal displacement of a foundation block
$u^f(\omega)$	surface amplitude of the free field ground motion
u_w	pore water pressure at the base of a slice
V	vertical load acting at the foundation underside
$v_{(l,t,r)}$	ground wave velocity; l – longitudinal wave, t – transversal wave, r - Reyleigh wave
W	nominal energy of impact hammer
W_c	nominal energy of vibratory drivers per cycle
w_d	width of the vibrating drum
W_e	explosive mass
W_s	weight of a slice, vibration source width
$X[k]$, $Y[k]$, $F[k]$	coefficients of a fast Fourier transform
$x[n]$, $y[n]$	odd and even members of $a[n]$
x_i	distance from impact
x_r	distance along the ground surface from the roller
z	Depth
Z_t	beam end displacement in time
ρ	unit density
B,Γ,β,β_t	tuning ratio
Δ_P	end displacement of a beam with fixed ends
Δt	time interval of a time series
$\partial\Delta_{w,l(t)}(\partial t)^{-1}$	ground particle velocity in longitudinal (l) and transversal (t) direction
$\Delta_{wr(o)}$	amplitude of displacement at distance (r) or at vibration source (o)
$\Delta\sigma_{v,z}$	vertical axial stress in soil at depth z
Ω_o	Fourier maximum displacement amplitude
$\Psi_{x,i,j}$	shape function of beam deflection (i,j) at a place i,j
α	angle of wave inclination to layer boundary or normal to the boundary
α_p	ground cohesion mobilization factor along pile shaft
α_s	inclination to the horizontal of the base of a slice

Symbol	Description
δ	small value of displacement, velocity, thickness etc.
δ_ϕ	friction angle between ground and pile shaft
ε_l	axial strain in longitudinal direction
ϕ	soil friction angle
γ	soil unit weight, shear strain
γ_d	dry unit weight of soil
γ_w	unit weight of water
κ	material attenuation coefficient
λ	wave length
ν	Poisson's ratio
θ	phase angle, angle of rotation of a foundation block
$\sigma'_{v(avr)}$	effective overburden pressure (avr, averaged over a depth)
$\sigma_{I,R,T}$	axial incident (I), reflected (R), transmitted (T) stress
σ_l	axial stress in longitudinal direction
σ_t	axial (tensile) stress
$\omega_{d,e,s,h,r}$	circular (angular) frequency (d) dumped, (e) equivalent, (s) structure, (h) in horizontal direction, (r) in rocking
$\xi_{e,g,s,h,r}$	damping ratio (e) equivalent (g) ground (s) structure (h) horizontal (r) rocking