Hans-Georg Kempfert
Berhane Gebreselassie

Excavations and Foundations in Soft Soils

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Berhane Gebreselassie

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With 421 Figures

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Herrn
Prof.Dr. Hans-Georg Kempfert
Universität Kassel
FG Geotechnik
Mönchebergstr. 7
34125 Kassel
Germany

Dr. Berhane Gebreselassie
Universität Kassel
FG Geotechnik
Mönchebergstr. 7
34125 Kassel
Germany

e-mail: geotech@uni-kassel.de

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Preface

The book is about soft soil engineering and is intended to serve the practicing as well as the research engineers. The planning, design and construction of excavations and foundations in soft to very soft soils is always a difficult and challanging assignment to engineers. The authors have tried to address some of these problems and challenges in this book.

Beside the state of the art of soft soils, authors own research results and experiences from practical projects are presented in the book. Special emphasis is also given among others on the presentation of several case studies coresponding to each topic treated in the book as well as a summary of the experiences in the determination of soil parameters for finite element analysis of geotechnical problems. The book is illustrated by a wealth of photographs and diagrams. The reader is refered to chapter 1 for a general introduction to the content of the book, the motives and backgrounds of the book.

The aim of the authors is to give the readers an overview of the state of the art of material properties of soft soils and their application in excavations, different types of foundations and stabilization methods. The authors emphasis, however, that the presence of soft soil in connection with construction measure should not a priori be classified as extremely difficult and strong cost intensive for the project. By making use of an advance knowledge in soft soil engineering so far available in the field of geotechnical engineering, it is possible to reach at a technically safe and economically justifiable solution for a particular construction project. The book is expected to contribute much in this regard.

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Hans-Georg Kempfert Berhane Gebreselassie

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Symbols and abbreviations

Here are the most frequently used symbols, abbreviations and expressions. Actually, most of the symbols has already been locally defined in the text. Some symbols may also have one or more definitions.

Geometrical symbols

Symbol	Description
A	pile spacing within a pile group
A_b	nominal value of pile base area
A_e, A_c	cross sectional area of a column, cross sectional area of an influence zone
A_Q	cross sectional area of pile
A_s	nominal value of pile shaft area
a_s	width of a pile with a square cross section
A_ε, A_ρ, A_μ	surface area at edge, at corner and in middle of a plate
b	width of an excavation
b, b_E, D_s, a_s	width or diameter of a single pile
d	distance behind a wall, thickness, diameter of a column
D	drainage path
D_b	pile base diameter
d_e	equivalent diameter
D_{eq}	equivalent pile diameter
D_s	pile shaft diameter
h	depth of excavation, height of soil specimen
Δh	thickness of a layer
h_0	reference height, initial height
h_B	depth to passive force from bottom of excavation
h_E	depth to active force from surface
L	pile length
L^*	elastic length of pile
l_d	drainage path
r_0	initial radius
r_c	equivalent radius of an influence zone of a single pile
R_c	column radius
S	settlement at pile head
s_d	column spacing
T	embedment into the bearing strata
Z	depth from ground surface, vertical deflection
z_c	depth to tension crack from surface

z_p	depth from bottom of excavation
z_P, z_W	vertical deflection of a pile and a soft layer

Material parameters

Symbol	Description
A, B	coefficient of pore pressure
A_f, B_f	coefficient of pore pressure at failure
$A_{f,s}$	coefficient of pore pressure at failure in standard triaxial compression test
C	composition
c	cohesion
c	wave propagation velocity
c_a	adhesion
C_B	Buisman factor
C_c	compression index
c_h	coefficient of consolidation in horizontal direction
C_p, C_w	subgrade reactions (spring constants) of pile and soft layer
C_s	swelling index
c_u	undrained shear strength
$c_{u,av}$	average shear strength along an assumed rupture surface
$c_{u,col}$	maximum value of undrained strength of a stabilising column
c_{uc}, c_{ut}	undrained shear strength in compression and in tension
c_{uv}, c_{uh}	undrained shear strength in vertical and horizontal directions
c_v	coefficient of compressibility
c_v	coefficient of consolidation in vertical direction
C_α	coefficient of secondary compression
$\underline{\underline{D}}^e$	elastic material stiffness matrix
$\underline{\underline{D}}^{ep}$	elasto - plastic stiffness matrix
$\underline{\underline{D}}$	tangential stiffness tensor of the material
E	drained modulus of elasticity
e	void ratio
$\overline{E}$	weighted average of the elasticity modulus of a column material and soil
e_0, e_p	initial void ratio
E_{50}	secant modulus of elasticity at 50% of deviator stress at failure (drained)
$E_{50(u)}$	secant modulus of elasticity at 50% of deviator stress at failure (undrained)
E_b	dynamic modulus of elasticity of pile material
E_h, E_v	modulus of elasticity in horizontal and vertical directions
E_i	initial tangent modulus of elasticity
e_L	void ratio at liquid limit
E_m	compressibility modulus
$E_{m,ur}$	compressibility modulus for un-/reloading
E_{oed}	constrained modulus of elasticity
$E_{oed,0}$	initial constrained modulus
$E_{oed,s}$	constrained modulus of the soft soil layer
$E_{oed,ur}$	constrained modulus of elasticity for un-/reloading
E^{ref}	reference drained modulus of elasticity

E_{sec}	secant modulus of elasticity
E_t	tangent modulus of elasticity
E_u	undrained modulus of elasticity
$E_{u,i}$	initial undrained modulus of elasticity
$E_{u,ur}$	undrained modulus of elasticity for un-/reloading
E_{ur}	modulus of elasticity for un/reloading
f_{bt}	tensile strength of a masonry wall
G	shear modulus
G^{ref}	reference shear stiffness at reference stress p^{ref}
G_s	specific gravity of a soil
G_s	shear modulus of unstabilised soil
G_{si}	undrained shear stiffness
G_u	undrained shear modulus
I_c	consistency index
I_D	relative density
I_L	liquidity index
I_p	plasticity index
I_v	viscosity index
$I_{v\alpha}$	coefficient of viscosity
J	stiffness of geosynthetic membrane
k	influence factor, dimensionless modulus number
k	coefficient of permeability of soil
K'	drained bulk modulus of elasticity
K_0	coefficient of earth pressure at rest
$K_{0(NC)}$, $K_{0(OC)}$	coefficient of earth pressure at rest for normally consolidated and overconsolidated soils
K_a	coefficient of active earth pressure
$K_{a,c}$	coefficient of active earth pressure of a column material in Rankin's special case
$\underline{\underline{K}}^{ep}$	elasto - plastic material stiffness in the finite element formulation
K_p	coefficient of passive earth pressure at limit state
K_a^T	ratio of total horizontal and vertical stresses in active state
K_p^T	ratio of total horizontal and vertical stresses in passive state
$K_{p,c}$	coefficient of passive earth pressure of a column material in Rankin's special case
K^{ref}	reference bulk modulus of elasticity
k_s	subgrade modulus on pile axis
K_u	bulk undrained modulus of elasticity
K_w	bulk modulus of water
LL	liquid limit
M	slope of critical state line in p - q diagram
m	stiffness exponent
M_c	compressibility modulus of columns
M_s	compressibility modulus of unstabilised soil
m_v	coefficient of compressibility for one-dimensional compression
OCR	overconsolidation ratio
PL	plastic limit
U	shape-factor
U_c	degree of consolidation

ΔV	volume change
w	water content of soil
$\overline{w}$	average water content of soil
W	total amount of slurry
w/c	water-cement ratio
W_p	amount of injected slurry
w_s	water content at shrinkage limit
Δw	water content difference
α_b	base resistance coefficient
α_k	shear coefficient
α_s	adhesion coefficient
β_s	settlement reduction factor
δ	wall friction
γ	unit weight of soil
γ'	buoyant unit weight of soil
γ_d	dry unit weight of soil
γ_D	unit weight of soil above the foundation level
γ_r, γ_{sat}	saturated unit weight of soil
γ_w	unit weight of water
φ	angel of internal friction
φ'_s	angel of overall shear strength
φ_u	undrained angel of internal friction
eqv. φ_{cu}	equivalent angel of total friction
φ'_c , φ'_t	effective angel of internal friction in compression and in tension
$\varphi'_{s,c}$, $\varphi'_{s,t}$	angle of overall shear strength in compression and extension
κ	slope of un/reloading line
κ^*	modified swelling index
λ	slope of normal consolidation line
λ^*	modified compression index
λ_{cu}	normalised undrained shear strength
$\lambda_{cu,s}$	normalised undrained shear strength in standard triaxial compression test
μ^*	modified creep index
ν	Poisson's ratio
ν'	drained Poisson's ratio
ν_u	undrained Poisson's ratio
ν_{ur}	Poisson's ratio for un/reloading
ν_v, ν_h	Poisson's ratio in vertical and horizontal direction
ρ	density of material
ρ_w	density of water dependent on temperature
τ	shear strength of soil
τ_{av}	average shear stress
τ_f	field vane shear strength
τ_m	mobilised shear strength
τ_n	negative skin friction
τ_{uv}, τ_{uh}	vane shear strength in vertical and horizontal directions
υ	specific volume

υ_c, υ_q, υ_γ	shape factors for cohesion
υ_{0i}, $\upsilon_{\kappa i}$	specific volume corresponding to p′=1 kN/m²
ψ	angle of dilatancy

Deformations, forces and stresses

Symbol	Description
$\underline{B}$	strain matrix
c_{ve}	equivalent coefficient of consolidation
$\boldsymbol{D}$	strain rate
de_e	recoverable elastic compression under constant effective stress
de_{ir}	irrecoverable compression under constant effective stress
de_v	irrecoverable viscous compression under constant effective stress
dp	incremental mean principal stress
dq	incremental shear stress
$d\varepsilon$	incremental strain
$d\underline{\varepsilon}$	incremental total strain tensor
$d\varepsilon_1$, $d\varepsilon_2$, $d\varepsilon_3$	incremental principal strains
$d\underline{\varepsilon}^e$	incremental elastic strain tensor
$d\underline{\varepsilon}^p$	incremental plastic strain tensor
$d\varepsilon_q$	incremental shear strain
$d\varepsilon_v$	incremental volumetric strain
$d\underline{\varepsilon}^{vp}$	incremental visco - plastic strain tensor
$d\underline{\sigma}$	incremental stress tensor
$d\sigma$	incremental stress
E	actions, effect of actions
e_{0h}, e_{0v}	earth pressure at rest in horizontal and vertical directions
e_{ah}, e_{av}	active earth pressure in horizontal and vertical directions
e_c	stress dependant critical void ratio
e_{c0}, e_{i0}, e_{d0}	limiting void ratios
E_h	characteristic horizontal load on a single pile
e_h, e_v	earth pressure in horizontal and vertical direction
e_i, e_d	stress dependant limiting void ratio
e_{ph}, e_{pv}	passive earth pressure in horizontal and vertical directions
F	force on pile head, stabilising actions
f	settlement coefficient
$F(\underline{\sigma})$,$F(\underline{\sigma},h)$	yield function
F_1	impact force
F_2	measured force of wave reflected at the base
f_c	skin friction of cone penetration test (CPT)
F_n	additional downdrag force on piles
ΔF_r	hoop tensile force in the geotextile coating
f_s	relative stress level, local skin friction
G	stabilising actions
G_{si}	initial shear stiffness

H	horizontal component of reaction forces
$h(d\underline{\varepsilon}^p)$	hardening function
h_s	granular hardening
I_1	the first invariant of the stress tensor
J_2	the second invariant of the deviatoric stress tensor
J_3	the third invariant of the deviatoric stress tensor
$k_{s,e}$, $k_{s,r}$, $k_{s,m}$	modulus of the subgrade reaction at the edge, at the corner and in the middle of the plate
p	surcharge load
p^*	existing stress level
p, p'	total and effective mean principal stresses
p_1^*, p_2^*	stresses before and after load change
p_f	characteristic flow-pressure
p_f, p'_f	total and effective mean principal stresses at failure
p'_m	previous maximum mean effective stress in which a soil was subjected
p'_t	mean stress at time t
p_{max}	absolute stress in surrounding soil at limit state
p_p	isotropic pre-consolidation stress
p^{ref}	reference pressure
q	deviatoric stress, total applied pressure (q_1+q_2)
Q, $Q(\underline{\sigma})$	potential function
q_1	pressure on columns
q_2	pressure on unstabilised soil
q_b	base resistance, point resistance, end bearing
$q_{b,l}$	ultimate base resistance
q_c	cone resistance
q_c	point resistance of cone penetration test (CPT)
Q^{col}	ultimate bearing capacity of a single column
q_f	deviatoric stress
q_s	shaft resistance
Q_S	shaft resistance for displacement piles
$q_{s,l}$	ultimate shaft resistance
$q_{s,l,t}$	ultimate shaft resistance in tension
$q_{s,t}$	shaft resistance in tension
q_t	deviatoric stress at time t
Q_T	total pile resistance for displacement piles
q_u	unconfined compressive strength
q_{ult}	ultimate asymptotic value of a deviatoric stress
Q_{ult}^{group}	total bearing capacity of a group of columns
R	resistance, aspect ratio of a cap
R_b	base resistance of a single pile
R_{cp}	resistance of end B2-columns
R_{dyn}	dynamic resistance
R_g	expected ultimate pile resistance
R_s	skin resistance of a single pile
R_{stat}	available static resistance
R_{tot}	total dynamic resistance
s	shear displacement

S	resultant tensile force in reinforcement membrane
s_0	immediate settlement
s_{ult}	settlement in ultimate limit state (ULS)
s_2	settlement of unstabilised soil
s_c	settlement of stabilising column, settlement of a foundation at a characteristic point
s_{cal}	calculated settlement
s_g	limit settlement
s_G	settlement due to group effect
s_p	consolidation settlement
s_s	settlement of the soil
s_{sg}	limit settlement for the settlement-dependent characteristic pile shaft resistance
s_∞	final settlement
s_z^{ES}	compression of an invalid column
s_B^{ES}	settlement of an invalid column
Δs	differential settlement
$\boldsymbol{T}$	stress tensor
$\overset{\circ}{\boldsymbol{T}}$	Jaumann stress rate as a function of stress level
u	pore water pressure
u_0	pore water pressure at steady state (hydrostatic), initial pore pressure
Δu	excess pore water pressure
Δu_f	excess pore water pressure at failure
W	strain energy density function
α	maximum angular rotation between two column rows
$\delta_v,\ \delta_v$	horizontal and vertical deflection of a wall
ε	strain
ε_f	strain at failure
ε_h	strain in horizontal direction
ε_{krit}	critical strain
ε_v	strain in vertical direction, volumetric strain
$\Delta\varepsilon$	change in strain
$\Delta\varepsilon_{vol}$	change in volumetric strain
$\dot{\varepsilon}$	rate of strain
$\dot{\varepsilon}_v$	porosity of a soil
$\dot{\varepsilon}_o$	strain rate at reference time t_0
$\dot{\varepsilon}_i$	strain rate at reference time t_i
λ	positive scalar of proportionality dependant on state of stress and load history
μ	fluidity parameter
$\underline{\sigma}$	stress tensor
$\sigma_{10},\ \sigma_{30}$	initial major and minor principal normal stress
$\sigma_c,\ \sigma_s$	pressures on column and soil
σ_{max}	ultimate load
σ_N	normal stress
$\sigma_{v,0,c}$	initial vertical stress in column
$\sigma_{v,0,s}$	initial vertical stress in soil

σ_x, σ_y	stresses in x- and y-directions
σ_{zo}	effective stress on top of soft soil layer
σ_Φ	tangential stress
σ'_{vc}	effective consolidation stress
σ'_h	effective horizontal stress
σ'_c	effective cell pressure
σ'_1	effective major principal stress
σ'_2	effective intermediate principal stress
σ'_3	effective minor principal stress
σ'_e	effective Hvorslev's equivalent stress
σ'_p	effective pre-consolidation pressure
σ'_0	effective net pressure on footing, contact pressure
σ'_b	effective stresses due dead and live loads from buildings
σ'_u	uplift pressure
σ'_A	constant effective stress
σ'_B	effective apparent pre-consolidation stress
$\sigma'_{v,max}$	maximum vertical effective pressure on column
$\sigma'_{h,max}$	maximum horizontal effective pressure on surrounding soil
$\sigma'_{h,0}$	effective initial horizontal stress in soil before column installation
σ'_m	effective mobilised stress
σ'_f	effective failure stress
σ'_r	effective radial stress
$\Delta\sigma'$	additional effective stress
$\dot{\sigma}_w$	rate of excess pore water pressure
σ'_{vm}	previous maximum vertical effective stress in which a soil was subjected
$(\sigma'_1 - \sigma'_3)_f$	deviator stress at failure in triaxial test
σ' , σ'_x	effective normal stress
σ_{v0} , σ'_{v0}	total and effective overburden pressures respectively
σ'_z , σ'_v	effective vertical stress
$\sigma'_{3,0}$, $\sigma'_{1,0}$	effective consolidation pressure in triaxial test
$\Delta\sigma_1$, $\Delta\sigma_3$	principal stress increaments
τ_{xy}	shear stress

Miscellaneous

Symbol	Description
a	factor to represent the calibration of the model on the Matsuoka-Nakaiyield function
a_c	area displacement ratio
C_1, C_2, C_3	constants
CAD	anisotropically consolidated drained
CAU	anisotropically consolidated undrained
CID	isotropically consolidated drained
CIU	isotropically consolidated undrained
C_r	shape factor
CPT	Cone penetration test
DSS	direct simple shear
EQU	loss of equilibrium of structures or ground
F.S	factor of safety against basal heave
F_d	factor of safety on the depth of penetration
f_d, f_e, f_b	factors to simulate the barotropy and pycnotropy effects
F_{np}	factor of safety on the moment of the net active forces
f_q, f_{wa}	safety factors on action forces and water pressure on the active side
F_r	factor of safety on the moment of activating forces
f_r, f_{wp}	safety factors on passive forces and water pressure
F_{sp}	factor of safety on the soil parameters for passive earth pressure
F_φ, F_c, F_{cu}	partial safety factors on friction φ, cohesion c and undrained strength c_{cu}
GEO	loss of failure of the ground (geotechnical failure)
GZ	limit state for German word “Grenzzustand”
HYD	hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradient
i_i, i_c	influence factor for the calculation of σ_z
index d	design value
index k	characteristic value
K	principal stress ratio
m	proportion of load carried by stabilising column
M	slope of the failure line in critical soil mechanics
N	number of load tests
n	proportionality constant, viscosity exponent, stress concentration factor, rate of the volumetric strain
N, N_b, N_c	stability number
N_{30}	number of blows for 30 cm penetration test
N_k	empirical cone factor
N_q, N_c, N_γ	bearing capacity factors
R^2	coefficient of correlation
R_f	failure stress ratio
R_{int}	interface element parameter (parameter reduction factor to account the wall friction and adhesion)
R_{inter}	interface factor
R_p, R_w	rotational speed of the mixing pool during penetration and withdrawal
SLS	serviceability limit state
SPT	Standard penetration test

STR	loss of structures or structural elements
T	blade rotation number
T^*	time from which viscosity starts to act
T, t	time
T_0	reference time
TC	triaxial compression
t_c	time required for primary consolidation
TE	triaxial extension
t_f	time to failure
t_i	time
t_p	primary consolidation time
tr	tensor
T_v	time factor
ULS	ultimate limit state
UPL	loss of equilibrium of structures, of elements of structures or ground due to uplift
UU	unconsolidated undrained
V	velocity
V_1	velocity of impact
V_2	velocity of wave reflected at the base
V_p, V_w	penetration and withdrawal velocity respectively
Z	impedance
Z(t)	time factor
ΣM	total number of mixing blades
α_k	shear coefficient
β	reciprocal of the gradient of the stress path
γ_{3D}	partial safety factor for passive resistance
γ_c	partial safety factor for cohesion
γ_{cp}	partial safety factor for load tests
γ_{dst}, γ_{stb}	partial safety factors for destabilising/stabilising actions
γ_F, γ_q	partial safety factor for actions or effect actions
γ_R, γ_r	partial safety factor for resistance
γ_{wa}	partial safety factor for water pressure
γ_φ	partial safety factor for angle internal friction
η_p	total safety factor on passive pressure
λ_{3D}	factor for three dimensional case
λ_t, λ_b, λ_c	bearing capacity coefficients
μ	empirical correction factor
μ_1, μ_2	the effect of the width of excavation
μ_A	anisotropic correction factor to the vane shear strength
μ_R	anisotropic and the rate of shearing correction factor to the vane shear strength
ω_b, $\omega_{s,q}$, $\omega_{s,f}$, $\omega_{s,s}$	empirical reduction factors
ξ	factor of anisotropy, correlation factor for evaluation of pile load tests