普通高等教育土建学科专业“十一五”规划教材
高校土木工程专业规划教材

# Underground Structures
# （地下建筑结构）

Edited By
Zixin Zhang & Xinyu Hu

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FIRST EDITION

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# *Preface*

Underground structures originated thousand years ago under the pressure of necessity. As the practical problems involving underground structures broadened in scope, the inadequacy of the scientific tools available for coping with them became increasingly apparent. Underground structures may be a tunnel, a shaft, or a cavern, either alone or a combination thereof. These texts were well received by instructors, students, and practitioners alike. The philosophy of the book was to include only items of utmost importance which will improve the quality of the final designed product, and will render a very cost effective design.

About seven years ago, there were several requests to prepare a single volume that was concise in nature but combined the essential components of underground structures. Nature is always smarter than some of us, and sometimes smarter than all of us. In response to those requests, the book was written for a broad spectrum of readers, ranging from engineers seeking technical guidance to owners and other decision makers hoping to glean a better understanding of alternatives. It included the fundamental concepts and methods of underground structures as well as underground engineering, including rock and soil tunnels, shafts, caverns, diaphragm walls and tunnelling methods.

Research into the development of underground structures and design has been extensive during the past five decades. Authors are tempted to include all of the recent developments in a text book; however, since this text is intended as an introductory text, it stresses the fundamental principles without becoming cluttered with too many details and alternatives. In the text itself, the authors have included cross-references to others chapters as appropriate. It is our hope that this combination will help readers locate information more quickly than a traditional, keyword-based index would.

Underground structures is abundantly illustrated to help students understand the material. Several examples are presented in related chapters. Problems are provided at the end of each chapter for homework assignment, and they are all SI units.

The authors have obviously devoted considerable effort to chapter preparation and they thank the various colleagues, publishers, websites and institutions who gave us permission to use and reproduce their copyrighted materials. Texts, tables and figures taken in whole or in part from various sources are acknowledged where they occur in the text.

The authors are especially indebted to Prof. Evert Hoek, Prof. M. Karakus, Specialist R. S. Sinha, Mr. R. J. Fowell, Prof. K. M. Lee, Prof. Xueyuan Hou, Dr. Yiming Sun, Prof. V. Gabriel Guzman and Prof. R. Kastner for their invaluable assistance and permission in preparing and revising the manuscript. Figures and tables from journals, proceedings, and books are reproduced with permission from the respective publishers.

We are grateful to CABP, the publisher for Civil Engineering, for their encouragement and understanding throughout the preparation and publication of the manuscript.

Activity is the only road to knowledge, we are slow walkers, but we never walk backwards.

*Zixin Zhang*

*Xinyu Hu*

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# Symbols

$A$ ($m^2$) = *area*

$A$ = *porewater-pressure coefficient*

$A_c$ = *activity* = $I_p/CF$

$B$ (m) = *width*

$C$ (*any dimension*) = *constant*

$C$ (kN) = *resultant cohesion*

$CF$ = *clay fraction*

$CRP$ = *constant rate of penetration*

$CRS$ = *constant rate of strain oedometer test*

$c$ (kPa) = *cohesion intercept*

$c$ (m/s) = *compression wave velocity*

$c'$ (kPa) = *cohesion intercept of Mohr-Coulomb failure envelope in terms of effective stress at failure*

$c$ (m) = *constant in Engineering News formula*

$c_v$ ($m^2$/year) = *coefficient of consolidation*

$c'$ (kPa) = *soil cohesion*

$c_u$ (kPa) = *undrained shear strength*

$D$ = *discharge factor* (*in relation to vertical drains*)

$D$ (m) = *depth*; *diameter*; *spacing between centers of piles*

$D$ (mm) = *grain size*

$D_{10}$ (mm) = *effective grain size*

$D_{50}$ (mm) = *mean grain size*

$D_e$ (mm) = *effective grain size*

$D_f$ (m) = *depth of foundation*

$D_r$ = *relative density of cohesionless soil*

$DS$ = *direct shear test*

$DSS$ = *direct simple shear test*

$d$ (m) = *distance*

$d$ (mm) = *grain size*

$d_b$ (m) = *base diameter of drilled shaft*

$d_s$ (m) = *shaft diameter of drilled shaft*

$E$ (kPa) = *modulus of elasticity*

$E$ (kN/m) = *normal force on side of slice* (*stability analysis*)

$E_i$ (kPa) = *initial tangent Young's modulus*

$E_s$ (kPa) = *modulus of deformation computed from pressuremeter measurement*

$E_u$ (kPa) = *undrained Young's modulus*

$EA$ (kN) = *Normal stiffness of pile or wall*

$EI$ (kN · m$^2$) = *flexural stiffness of pile or wall*

$E$ (kPa) = *Young's modulus of tunnel lining (ML-1T-2)*

$(EI)_e$(kN · m$^2$/m) = *effective bending rigidity per unit length of a segmental tunnel*

$EI$ (kN · m$^2$/m) = *bending rigidity per unit length of the actual tunnel lining*

*ESSA* = *effective stress stability analysis*

$e$ = *void ratio*

$e_o$ = *initial void ratio*

$F$ (kN) = *reaction; resultant force*

$F$ = *factor of safety*

*FS* = *factor of safety*

$f$ = *coefficient of friction between soil and base of structure*

$f_k$(kPa) = *physical index of rock mass*

$G$ = *shear modulus; also, specific gravity*

GPa = $10^3$ MPa

$g$ (gal) = *acceleration due to gravity*

$H$ (m) = *thickness of stratum*

$h$ (m) = *thickness of the soil layer*

$h_i$(m) = *thickness of the soil layer i*

*IL* = *incremental loading oedometer test*

$I$ = *Moment of inertia of area*

$I_l$ = *liquidity index*

$I_p$ = *plasticity index*

$I_z$ = *vertical strain influence factor*

$I_1$, $I_2$, $I_3$ = *invariants of stress*

$I$ (m$^4$/m) = *moment of inertia per unit length of tunnel lining*

$I_e$(m$^4$/m) = *effective moment of inertia per unit length of tunnel lining*

$I_j$(m$^4$/m) = *moment of inertia per unit length at the joint*

$I_L$ = *liquidity index*

$i$ = *hydraulic gradient*

$i$ = *angle of the leading edge of an asperity on a joint*

$i_p$(kN/m$^3$) = *pressure gradient*

$J_n$ = *joint set number*

$J_r$ = *joint roughness number*

$J_a$ = *joint alteration number*

$J_w$ = *joint water reduction factor*

$K$ = *ratio between intensities of effective horizontal and effective vertical pressures at a given point in a mass of soil*

$K_0$ = *coefficient of earth pressure at rest (value of K for initial state of equilibrium)*

$K_{op}$ = *coefficient of earth pressure at rest in normally consolidated young deposits*

$K_a$ = *coefficient of active earth pressure*

$K_p$ = *coefficient of passive earth pressure*

$K_{ps}$ = *coefficient of passive earth pressure during passive shearing*

$K$ (kPa) = *bulk modulus of soil skeleton*

$K$ (kPa/m) = *spring stiffness*

$K_h$(kPa/m) = *modulus of horizontal subgrade reaction*

$K_s$(kPa/m) = *coefficient of soil resistanc; coefficient of subgrade reaction*

$K$ = *coefficient of earth pressure*

$K_0$ = *coefficient of earth pressure at rest*

$K_s$(kN/m$^3$) = *soil resistance coefficient*

$K_\theta$(kN · m/(rad · m)) = *flexural stiffness of a joint per unit length*

$k$ (m/s) = *coefficient of permeability*

$l$ (m) = *length*

$l$ (m) = *calculation length of a tunnel (usually adopted as 1 m)*

$M_c$(kN/m) = *moment of cohesive forces*

$M$ (kN · m/m) = *bending moment per unit length in tunnel lining*

$M_p$(kN · m/m) = *bending moment per unit length due to surrounding earth pressures*

$M_{pj}$(kN · m/m) = *bending moment per unit length under the jth loading case*

$\overline{M}$ = *internal bending moment per unit length due to a dimensionless unit force*

MPa = *megapascals* (MN/m$^2$)

$N$ = *dimensionless factor*

$N_b$ = *base stability number*

$N_c$ = *equivalent significant number of uniform shearstress pulses produced by earthquake or imposed in the laboratory*

$n$ = *porosity*

$n_a$ = *ratio between distance from bottom of lateral support to point of application of earth pressure and total height of lateral support*

$n_d$ = *depth factor (stability of slopes)*

$n_h$(kPa/m) = *coefficient of horizontal subgrade reaction*

$n_o$ = *initial porosity*

$n$ = *number of joints in the tunnel half ring*

$N$ (kN/m) = *axial force per unit length in the tunnel lining*

$\overline{N}$ = *axial force per unit length due to a dimensionless unit force*

$N_p$(kN/m) = *axial force per unit length due to surrounding earth pressures*

$N_{pj}$(kN/m) = *axial force per unit length under the jth loading case*

$OCR$ = *overconsolidation ratio* $= \sigma'_p/\sigma'_{vo} = \sigma'_{vmax}/\sigma'_{vo}$

$P$ = *percent of grains smaller than given size*

$P$ (kN or kN/m) = *resultant pressure, normal force*

$P_A$(kN/m) = *active earth pressure if arching is absent (retaining wall; active Rankine state)*

$PCPT$ = *push cone penetration test*

$P_I$ = *plasticity index*

$p_1$(kPa) = *vertical overburden earth pressure at the tunnel crown*

$p_2$(kPa) = *reaction pressure at the bottom of tunnel lining*

$p_3$(kPa) = *total lateral earth pressure at the crown level of tunnel lining*

$p_4$(kPa) = *additional earth pressure developed at the tunnel invert level*

$p_5$(kPa) = *self-weight of the tunnel lining*

$p_6$(kPa) = *lateral soil resistance pressure*

$p$ (kPa) = *surrounding earth pressure around a tunnel*

$p_h$(kPa) = *value of p along the horizontal axis of the tunnel*

$p_v$(kPa) = *value of p along the vertical axis of the tunnel*

$p_r$(kPa) = *soil resistance developed at the springline of a tunnel*

$P$ (kN/m) = *applied vertical load (MT-2)*

$P_a$(kN/m) = *active earth pressure if arching is present (bracing in open cuts)*

$P_0$(kN) = *Surcharge*

$P_p$(kN/m) = *passive earth pressure (May be subdivided into $[P_P]_{II}$, which depends on cohesion and surcharge.)*

$P_s$(kN) = *resultant of forces having seat on surface of particle*

$P_w$(kN/m) = *resultant water pressure*

$p$ (kPa) = *pressure of normal stress; subgrade reaction*

$p'$ (kPa) = *effective stress* = $(\sigma_1' + \sigma_3')/2$

$p_A$(kPa) = *intensity of active earth pressure*

$p_L$(kPa) = *limiting pressure reached in pressuremeter*

$p_q$(kPa) = *increase in pressure on retaining wall due to surcharge q per unit of area*

$p_{q1}$(kN/m) = *increase in pressure on retaining wall due to surcharge $q_1$ per unit of length parallel to crest*

$p_s$(kPa) = *swelling pressure*

$p_1$, $p_2$(kPa) = *secondary principal stresses*

$Q$ (kN) = *concentrated load; strut load*

$q_1$(kPa) = *total earth pressure developed above tunnel level*

$q_2$(kPa) = *total earth pressure developed at the shoulder regions of a tunnel*

$\overline{Q}$ = *shear force per unit length due to a dimensionless unit force*

$Q_p$(kN/m) = *shear force per unit length due to surrounding earth pressures*

$Q_{pj}$(kN/m) = *shear force per unit length under the jth loading case*

$q$ (kPa) = *average gross bearing pressure over the foundation*

$q$ (kPa) = *shear stress* = $(\sigma_1 - \sigma_3)/2$

$q$ (kPa) = *uniformly distributed load*; *surcharge per unit of area*; *uniformly distributed line load*

$q$ ($m^3$/day) = *seepage rate or flow rate*

$q_a$ (kPa) = *allowable soil pressure*

$q_c$ (kPa) = *the pressure at which the material passes from the elastic into the semiplastic or plastic state*

$q_f$ (kPa) = *bearing capacity*

$q_t$ (kPa) = *cone tip resistance*

$q_u$ (kPa) = *unconfined compressive strength*

$R$ = *ratio of size of filter material to size of material to be protected*

$R$ (m) = *radius of influence of well*; *radius of curvature of deformed slope*

$R_c$ = *uniaxial compression strength*

$R_f$ = *parameter used in hyperbolic stress strain equation*

$R_s$ = *total surcharge ratio*

$R'_s$ = *effective surcharge ratio*

*RMR* = *rock mass rating according to the Geomechanics Classification*

*RQD* = *Rock Quality Designation*

$R$ (m) = *tunnel calculation radius defined as the average of outer* ($R_0$) *and the inner* ($R_i$) *radii* ($L$)

$R_d$ = *displacement ratio*

$R_{hd}$ = *horizontal displacement ratio*

$R_{vd}$ = *vertical displacement ratio*

$r$ (m) = *radius*

$r_0$ = *radius of logarithmic spiral*

$S$ (kN/m) = *total sliding resistance between base of dam and subsoil*

$S$ (mm) = *settlement*; *heave*; *penetration of pile under hammer blow*

$S$ = *shear wave*

$S$ = *spacing between joints of a given set*

*SML* = *slow maintained load*

*SRF* = *stress reduction factor*

$S_c$ (mm) = *settlement at end of construction and application of permanent live load*

$S_i$ (kPa) = *shear strength intercept according to the Mohr Coulomb relationship* ('*cohesion*')

$S_j$ (kPa) = *shear strength intercept for a joint*

$S_p$ (mm) = *settlement at end-of-primary consolidation*

$S_r$ = *degree of saturation*

$S_t$ = *degree of sensitivity*

*SQD* = *specimen quality designation*

$s$ (kPa) = *shearing resistance*; *shear strength*; *drained shear strength*

$s_u$ (kPa) = *undrained shear strength*

$s_u$(*critical*) (kPa) = *undrained shear strength of liquefied sand*

$s_u(mob)$ (kPa) = *undrained shear strength mobilized in full-scale field failures; undrained shear strength mobilized during stage construction*

$s_{uo}(DSS)$ (kPa) = *preconstruction undrained shear strength measured by direct simple shear test*

$s_{uo}(FV)$ (kPa) = *preconstruction undrained shear strength measured by field vane test*

$s_{uo}(TC)$ (kPa) = *preconstruction undrained shear strength measured by triaxial compression test*

$s_{uo}(TE)$ (kPa) = *preconstruction undrained shear strength measured by triaxial extension test*

$s_{uo}(UC)$ (kPa) = *preconstruction undrained shear strength measured in unconfined compression test*

$s_{uo}(UU)$ (kPa) = *preconstruction undrained shear strength from unconsolidated undrained compression test*

$s_{uo}$ (kPa) = *preconstruction undrained shear strength*

$T$ (kN/m) = *shear force on side of slice (stability analysis)*

$T$ (*degrees centigrade*) = *temperature*

$T_c$ = *construction time factor*

$T_{MR}$ = *magnitude of the flexural tensile strength ("modulus of rupture")*

$T_r$ = *time factor for radial consolidation (vertical compression with radial flow)*

$T_v$ = *time factor for one-dimensional consolidation in vertical direction*

$T_0$ = *magnitude of the tensile strength; uniaxial tensile strength unless indicated other wise*

$TC$ = *triaxial compression test*

$TE$ = *triaxial extension test*

$t$ (s) = *time* $t$ (m) = *thickness of the tunnel lining*

$t$ (m) = *thickness of the tunnel lining*

$t_c$ (days) = *construction time*

$U$ = *average degree of consolidation*

$UU$ = *unconsolidated undrained triaxial compression test*

$USSA$ = *undrained strength stability analysis*

$u$ (kPa) = *porewater pressure*

$u$, $v$ (m) = *displacements parallel to* $x$, $y$; *positive in positive direction of coordinate axis*

$u_r$, $u_\theta$ = *displacements parallel to* $r, \theta$

$\Delta u$ (mm) = *shear displacement along a joint; also radial deformation*

$\Delta h$ (mm) = *the horizontal displacement of the tunnel lining at the springline level*

$\Delta v$ (mm) = *normal displacement across a joint*

$\Delta_h'$ (m) = *predicted horizontal displacement of the equivalent tunnel by matching the vertical displacement in the equivalent process*

$\Delta_{ip}$ (m) = *displacement developed at the location of the redundant force xi due to the action of surrounding earth pressures*

$\Delta_v$ (m) = *vertical displacement of a tunnel defined as the total change of the tunnel diameter in the vertical direction*

$\Delta_v'$ (m) = *predicted vertical displacement of the equivalent tunnel by matching the horizontal displacement in the equivalent process*

$V$ (m$^3$) = *total volume*

$\nu_s$ = *Poisson's ratio of soil*

$W$ (kN or kN/m) = *weight*

$w$ = *water content in percent of dry weight*

$w_l$ = *liquid limit*

$w_o$ = *natural water content in percent of dry weight*

$w_p$ = *plastic limit*

$w_s$ = *shrinkage limit*

$x$, $y$, $z$ = *right-handed Cartesian coordinates*

$z$ (m) = *depth, position, or elevation head*

$z_c$ (m) = *depth of tension cracks*

$\alpha$ = *angle*

$\alpha$ = *pressuremeter rheological coefficient*

$\alpha$ = *reduction factor on strength of clay adjacent to shaft of pier*

$\beta$ (degrees) = *slope angle*

$\gamma$ (kN/m$^3$) = *total unit weight*

$\gamma'$ (kN/m$^3$) = *submerged unit weight*

$\gamma_c$ (kN/m$^3$) = *average unit weight of the comcrete (lining material, etc.)*

$\gamma_d$ (kN/m$^3$) = *dry unit weight, unit weight of soil if water is entirely replaced by air*

$\gamma_w$ (kN/m$^3$) = *unit weight of water*

$\gamma_s$ (kN/m$^3$) = *average unit weight of solid constituents*

$\gamma_{sat}$ (kN/m$^3$) = *unit weight in saturated state*

$\gamma_i$ (kN/m$^3$) = *total unit weight of soil layer i*

$\gamma_{as}$ (kN/m$^3$) = *average total unit weight of soil at the shoulder regions*

$\gamma_c$ (kN/m$^3$) = *unit weight of lining material*

$\gamma_w$ (kN/m$^3$) = *unit weight of water*

$\Delta$ = *change*

$\delta$ (degrees) = *angle of wall friction; angle between resultant stress on plane and normal to plane*

$\delta$ (mm) = *displacement at a point of rock mass*

$\delta_h$ (mm) = *lateral movement*

$\delta_{hmax}$ (mm) = *maximum lateral movement*

$\delta_{ii}$ = *displacement developed at the location of the redundant force xi and displacing in the same direction as xi due to the action of a dimensionless unit force* $x_i = 1$

$\delta_{ij}$ = *displacement developed at the location of the redundant force xi and along the direction of xi due to the action of a dimensionless unit force* $x_j = 1$

$\varepsilon$ = *base of Naperian logarithms; unit strain*

$\varepsilon_c$ = *compression strain index*

$\varepsilon_f$ = *axial strain at failure*

$\varepsilon_R$ = *reference strain*

$\varepsilon_v$ = *vertical strain*

$\varepsilon_\alpha$ = *secondary compression strain index*

$\eta$ (kN/m$^2$) = *effective bending rigidity ratio, viscosity*

$\theta$ (degrees) = *angle; central angle*

$\lambda$ = *joint stiffness ratio; coefficient of the lateral pressure; creep patameter*

$\mu$ = *Poisson's ration; field vane correction factor for embankment and foundation stability analysis; micron; friction coefficient* (= tan$\phi$); *also same as* $\eta$

$\mu_{UC}$ = *correction factor for unconfined compression test on specimens from D to B quality*

$\mu_s$ = *field vane correction factor for slope stability analysis*

$\mu_t$ = *time-to-failure correction factor for undrained shear strength from laboratory tests*

$\upsilon$ = *Poisson's ration*

$\rho$ = *mass density* ($FL^{-4}T^2$)

$\rho_d$ (Mg/m$^3$) = *density in dry state*

$\rho_s$ (Mg/m$^3$) = *average density of solid constituents*

$\rho_{sat}$ (Mg/m$^3$) = *density in saturated state*

$\rho_w$ (Mg/m$^3$) = *density of water*

$\sigma$ (kPa) = *total normal stress, normal stress at the cross section of the tunnel lining*

$\sigma_g$ (kPa) = *normal grout stress*

$\sigma'$ (kPa) = *effective normal stress*

$\sigma_1$ (kPa) = *major principal stress*

$\sigma_2$ (kPa) = *intermediate principal stress*

$\sigma_3$ (kPa) = *minor principal stress*

$\sigma'_1$ (kPa) = *effective major principal stress*

$\sigma'_2$ (kPa) = *effective intermediate principal stress*

$\sigma'_3$ (kPa) = *effective minor principal stress*

$\sigma'_c$ (kPa) = *preconsolidation pressure or critical pressure resulting from secondary compression*

$\sigma'_{1c}$ (kPa) = *effective major principal stress after consolidation and before undrained shear*

$\sigma'_{3c}$ (kPa) = *effective minor principal stress after consolidation and before undrained shear*

$\sigma'_{\alpha o}$ (kPa) = *in suti effective normal stress on a plane with orientation* $\alpha$ *to the horizontal*

$\sigma'_h$ (kPa) = *effective horizontal pressure*

$\sigma'_n$ (kPa) = *effective normal stress on a plane*

$\sigma'_p$ (kPa) = *preconsolidation pressure*

$\sigma'_{pl}$ (kPa) = *preconsolidation pressure measured in isotropic consolidation test*

$\sigma'_s$ (kPa) = *isotropic effective stress in an undisturbed specimen*

$\sigma'_v$ (kPa) = *total vertical stress*

$\sigma'_{vc}$ (kPa) = *vertical consolidation pressure*

$\sigma'_{vcr}$ (kPa) = *critical pressure at which the bearing plate on unsaturated soils with metastable struc-*

*ture plunged into the ground*

$\sigma_{vf}$ (kPa) = *postconstruction total vertical stress*

$\sigma'_{vf}$ (kPa) = *final effective vertical stress* = $\sigma'_{vo} + \Delta\sigma'_{v}$

$\sigma'_{max}$ (kPa) = *maximum past pressure*

$\sigma_{vo}$ (kPa) = *preconstruction total vertical stress*

$\sigma'_{vo}$ (kPa) = *in situ effective vertical stress, effective overburden pressure*

$\sigma'_{vs}$ (kPa) = *maximum effective vertical stress reached before the removal of surcharge*

$\Delta\sigma_{a}$ (kPa) = *axial stress imposed during the second step of a triaxial test*

$\tau$ (kPa) = *shear stress*

$\tau$ (*seismic*) (kPa) = *equivalent uniform shear stress pulse produced by an earthquake*

$\tau_{c}$ (kPa) = *shear stress carried by soil after consolidation and before undrained shear*

$\tau_{h}$ (kPa) = *shear stress on horizontal planes*

$\tau_{max}$ (kPa) = *maximum shear stress pulse produced by an earthquake*

$\tau_{r\theta}$ (kPa) = *the shear stress in the radial of tangential direction, at any point of ground*

$\tau_{s}$ (kPa) = *shear stress applied under undrained conditions followed by consolidation*

$\tau_{v}$ (kPa) = *shear stress on vertical planes*

$\tau_{\alpha o}$ (kPa) = *in situ shear stress on a plane with orientation* $\alpha$ *to the horizontal*

$\Phi$ = *velocity potential (flow net)*

$\phi'$ (degree) = *effective-stress friction angel; effective internal friction angle of soil; angle of shearing resistance*

$\phi'_{cv}$ (degree) = *constant-volume friction angle*

$\phi'_{d}$ (degree) = *component of friction angle produced by dilation*

$\phi'_{g}$ (degree) = *component of friction angle of granular soils resulting from geometrical interference*

$\phi'_{j}$ = *friction angle for a joint*

$\phi'_{m}$ (degree) = *effective-stress friction angle mobilized at undrained yield condition*

$\phi'_{p}$ (degree) = *component of friction angle of granular soils resulting from particle rearrangement*

$\phi'_{s}$ (degree) = *secant friction angle for granular soils*

$\phi'_{\mu}$ (degree) = *angle of interparticle sliding friction*

$\varphi$ (degree) = *internal friction angle of soil/rock*

$\psi$ (degrees) = *angle of dilatancy*

$\Psi$ = *function defining flow lines; angle between the direction of* $\sigma_1$ *and the plane of a joint*

$\bar{\omega}$ = *average displacement of a bearing plate*

$\omega$ (%) = *moisture content of the soil*

ln*a* = *Naperian (natural) logarithm of a*

log*a* = *logarithm of a to the base* 10

$x_1$ (kN · m/m) = *bending moment per unit length acting at the tunnel crown*

$x_2$ (kN · m/m) = *axial force per unit length acting at the tunnel crown*

# *Contents*