Integrated Modelling of Structure-Foundation Systems

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ABSTRACT

A problem endemic in the development of the built environment is poor communication between structural and geotechnical specialists. Through better communication and considering the structure and foundation as an integrated system, new opportunities may arise for achieving superior performance. This thesis investigates the seismic performance of the integrated system through the development of integrated structure-foundation models using the Ruaumoko structural analysis program.

A detailed representation of the structural and foundation systems was created using Ruaumoko, providing insight into the response of a range of integrated structure-foundation systems during seismic loading. In developing both shallow and deep foundation models, some modifications were made to Ruaumoko elements in order to improve the foundation model, but generally existing element configurations were used to represent foundations. Multiple structural and foundation designs were developed using a range of approaches.

Use of a range of shallow foundation design methods identified the significant impact that moment loading had on foundation performance. Partial uplift of footings was identified as detrimental to footing performance as it shifted the rotational axes, increasing moment loads and reducing effective footing area. Pinned connections between the structure and shallow footings eliminated these effects at the expense of significant redistribution of actions in the structure and increased displacements. Variation of soil conditions showed that softer soil was most likely to reduce demands on the structure at the expense of foundation non-linearity.

Reduced stiffness and increased radiation damping characteristics of raft foundations compared to footing foundation systems reduced the demands on three storey structures for all soil conditions. Increased structural demands were identified for the ten storey structure as a result of the reduced impact of foundation characteristics on the response of the integrated system.

The level of rotational restraint at the head of pile foundations had a considerable effect on the structure and the foundation, with free-head piles developing the largest pile displacements and actions. Reduced rotational stiffness caused a substantial change in the distribution of structural actions, while increasing rotational restraint moved the characteristics closer to the response of fixed base models. Softer soil conditions greatly increased non-linearity in the foundation soil without any definitive improvement in structural performance.

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NOTATION

Roman characters:

a	horizontal ground acceleration
A	amplitude of cycle of free vibration
A'	effective area of shallow foundation
a_0	parameter for dynamic characteristics of shallow foundation
A_b	area of shallow foundation base/pile foundation end
A_{bT}	tributary foundation base area of each foundation spring
A_{end}	area of end of shallow foundation perpendicular to movement
A_g	gross cross-sectional area of structural member
A_h	area of the transverse reinforcement of pile section
A_p	area of contact between soil and shallow foundation parallel to movement
A_{pT}	tributary area of contact between soil and shallow foundation parallel to movement for each foundation spring
A_s	sidewall-soil contact area for shallow foundation
B	footing width
B'	effective width of shallow foundation
$C(T)$	elastic site hazard spectrum
c	soil cohesion
$\mathbf{C}$	damping matrix
$\bar{c}_1$	shallow foundation radiation damping factor
$C_d(T)$	horizontal design response spectrum
C_{eff}	effective dashpot coefficient value
$C_h(T)$	spectral shape factor
c_H	total horizontal radiation damping coefficient for pile foundation
$C_{H,emb}$	horizontal damping for shallow foundation
$C_{radiation}$	radiation damping of a shallow foundation
cr_D	tension crack width adjacent to pile at depth z
cr_G	tension crack width adjacent to pile at ground surface
cr_{tot}	final tension crack width at ground surface
$\bar{c}_{rx}$	rotational radiation damping factor for shallow foundation
C_T	total damping of shallow foundation

C_{tot}	total dashpot coefficient value
c_v	vertical soil radiation damping coefficient for pile foundation
$C_{V,emb}$	vertical radiation damping for shallow foundation
$\bar{c}_y$	horizontal radiation damping factor for shallow foundation
$\bar{c}_z$	vertical radiation damping factor for shallow foundation
$C_{\theta,emb}$	rotational radiation damping for shallow foundation
d	height of soil contact on side of shallow foundation
D	pile diameter
D'	effective diameter of pile concrete core to centre of transverse reinforcement
D_f	depth of shallow foundation
d_{Mmax}	depth to maximum moment
e	eccentricity of loading on a shallow foundation
E_c	modulus of elasticity of concrete
EI	flexural rigidity of structural member
E_p	modulus of elasticity of pile material
E_s	Young's modulus of soil
E_{st}	modulus of elasticity of structural element
E_u	earthquake structural action for ultimate limit state
e_x	eccentricity of loading on a shallow foundation in the width direction
e_y	eccentricity of loading on a shallow foundation in the length direction
F	modal forces at each floor level
$\bar{F}$	normalised parameter for soil inertia forces
F_1	fundamental frequency of soil profile
f_c	natural frequency of compressing mode of soil stratum
f'_c	unconfined compressive strength of concrete
F_{con}	frequency parameter for kinematic interaction
FOS_{BC}	bearing capacity factor of safety of shallow foundation
$F_{passive}$	peak passive resistance of end of shallow foundation
F_{pre}	compressive force applied to pile soil springs
f_s	natural frequency of shearing mode of soil stratum
f_s	ultimate side frictional stress of pile
F_{shear}	peak shear resistance of shallow foundation
f_t	tensile strength of concrete
F_{ult}	ultimate load of a shallow foundation

f_{ultH}	ultimate horizontal load for individual springs for shallow foundation
F_{ultH}	ultimate horizontal load of a shallow foundation
f_{ultV}	ultimate vertical load for individual vertical springs for a shallow foundation
F_{ultV}	ultimate vertical load of a shallow foundation
f_{yh}	yield strength of transverse reinforcement
g	final gap width adjacent to pile at ground surface
G	imposed structural action
g_{fd}	final gap width adjacent to pile at depth z
G_s	soil shear modulus
G_{st}	shear modulus of structural section
H	thickness of soil layer
H_c	shear strength provided by concrete in pile section
h_e	effective height of structure
h_f	depth to centre of shallow foundation
H_f	horizontal load on foundation
H_{fn}	nominal shear strength of pile section
h_n	height from base of structure to uppermost seismic weight
H_s	shear strength provided by reinforcement in pile section
H_u	Brom's ultimate lateral capacity of pile
I_{bx}	moment of inertia of shallow foundation about short axis
I_D	moment of inertia of strip of shallow foundation
I_{depthH}	foundation embedment depth influence factor for horizontal stiffness
I_{depthV}	foundation embedment depth influence factor for vertical stiffness
I_e	effective moment of inertia of structural member
I_{exx}	effective moment of inertia of structural member about x axis
I_{eyy}	effective moment of inertia of structural member about y axis
I_g	gross moment of inertia of structural member
I_p	moment of inertia of pile section
I_{shapeH}	foundation shape influence factor for horizontal stiffness
I_{shapeV}	foundation shape influence factor for vertical stiffness
$I_{sidewallH}$	foundation sidewall influence factor for horizontal stiffness
$I_{sidewallV}$	foundation sidewall influence factor for vertical stiffness
I_U	kinematic interaction factor for horizontal displacement
$k(a_0)$	soil dynamic stiffness coefficient

$K(a_0)$	dynamic stiffness of shallow foundation
k	modulus of subgrade reaction
K	stiffness ratio
$\mathbf{K}$	stiffness matrix
K_0	coefficient of earth pressure at rest
k_1	record scale factor for earthquake scaling
k_2	family scale factor for earthquake scaling
K_{basic}	stiffness of a strip foundation on the ground surface
K_E	initial elastic stiffness of foundation
$K_{embedded}$	stiffness of an embedded footing
k_{end}	stiffness of the end zone of the FEMA273 shallow foundation model
k_H	horizontal stiffness of individual springs in foundation spring bed
K_H	horizontal stiffness of foundation
$K_{Hsurface}$	horizontal stiffness of a strip foundation on the ground surface
k_i	stiffness of individual springs in foundation spring bed
k_{mid}	stiffness of the middle zone of the FEMA273 shallow foundation model
k_{os}	small strain coefficient of subgrade reaction of soil
k_{out}	stiffness of the outer soil spring for pile at each depth
k_s	coefficient of subgrade reaction
K_S	horizontal stiffness of structure
K_{static}	static stiffness of shallow foundation
k_{tot}	total stiffness of the soil spring for pile at each depth
k_V	vertical stiffness of individual springs in foundation spring bed
K_v	vertical stiffness of foundation
$K_{Vsurface}$	vertical stiffness of a strip foundation on the ground surface
k_θ	rotational stiffness of individual springs in foundation spring bed
K_θ	rotational stiffness of foundation
$K_{\theta F}$	total rotational stiffness of foundation system
$K_{\theta R}$	rotational stiffness of foundation reduced for rotational stiffness developed by vertical spring bed
$K_{\theta surface}$	rotational stiffness of a strip foundation on the ground surface
k_μ	factor for determining the ultimate limit state for the horizontal design response spectrum
L	footing length

L'	effective length of shallow foundation
L_{ave}	lever arm to centre of shallow foundation/strip of shallow foundation
l_c	active pile length
Le	equivalent span of structural beams
L_{in}	inner boundary of strip of shallow foundation
L_{out}	outer boundary of strip of shallow foundation
L_r	length to diameter ratio of pile foundation
L_t	tributary length of pile for each soil spring
M(z)	pile moment with depth
m	mass applied to nodal points
M	bending moment of structural section
M	mass matrix
MB	beam column yield surface yield moment about at balance point
M_{cr}	moment at which tensile strength of extreme concrete reached
M_{end}	fixed end moment at end of structural beams
M_f	moment load on foundation
M_{fn}	nominal flexural strength of pile section
M_m	floor mass
MPF	modal participation factor
M_{sd}	moment at foundation level
M_{tot}	total seismic mass of structure
M_x	moment load on a shallow foundation about the width dimension
M_y	moment load on a shallow foundation about the length dimension
M_y^+	positive beam yield moment
M_y^-	negative beam yield moment
N(T,D)	near fault factor
n	curvature parameter of p-y relationship
N^*	axial load on column
NF	Modified Takeda reloading stiffness power factor
N_c	bearing capacity factor
N_k	bearing capacity factor
N_{max}	ultimate bearing capacity of the foundation under a vertical centred load
N_p	pile lateral bearing capacity factor
N_q	bearing capacity factor

N_{sd}	vertical load at foundation level
N_γ	bearing capacity factor
p	lateral soil resistance per unit length of pile
P_{av}	average soil pressure on pile perimeter
Pb	beam column yield surface axial compression force at balance point
Pc	beam column yield surface axial compression yield force
P_l	perimeter of the pile section
Pt	beam column yield surface axial tension yield force
P_{tot}	total confinement pressure from soil and internal transverse reinforcement
p_{ult}	limiting lateral pressure of p-y relationship
q	surcharge pressure on a shallow foundation
Q	imposed structural action
q_c	CPT tip resistance
q_{dis}	distributed load on structural beams
q_p	ultimate point resistance of pile
Q_p	ultimate vertical capacity of pile end
Q_s	ultimate vertical capacity of pile shaft
q_u	gross ultimate bearing pressure of a shallow foundation
Q_u	seismic imposed structural action for ultimate limit state
Q_u	ultimate vertical capacity of pile
r	post-yield slope factor
r_t	ratio of inner and outer spring stiffness for series radiation damping model
R	return period factor
r_{sec}	radius of pile section
S(z)	pile shear with depth
s	spacing of transverse reinforcement
S_A	design lateral acceleration coefficient or spectral acceleration
$SA_{component}$	spectral acceleration of earthquake record at a certain period
SA_{target}	spectral acceleration of elastic site hazard spectrum at a certain period
s_{eff}	effective spacing of transverse reinforcement
S_p	structural performance factor
s_u	soil undrained shear strength
S_θ	foundation shape influence factor for rotational stiffness
T	natural period of structure

$\overline{T}$	natural period of equivalent SDOF structure-foundation system
u_{com}	horizontal displacement of centre of mass of floor
$u_{inelastic}$	inelastic horizontal displacement of centre of mass of floor
V	shear force on structural section
V_f	vertical load on foundation
V_{foot}	volume of footing
V_{La}	apparent velocity of soil compression waves
V_s	soil shear wave velocity
V_{sd}	horizontal load at foundation level
W_{deck}	weight of bridge superstructure
W_{foot}	weight of footing
W_{pile}	weight of pile
y(z)	horizontal displacement of pile shaft with depth
y	horizontal (lateral) deflection of pile
y_{50}	lateral deflection at 0.5 p_{ult}
Y_{max}	maximum modal displacement
$\ddot{Y}_{max}$	maximum modal acceleration
z	depth from ground surface down pile
Z	hazard factor

Greek characters:

α	Modified Takeda unloading stiffness factor
α_r	Rayleigh damping mass coefficient
α_a	soil adhesion factor
β	Modified Takeda reloading stiffness factor
β_{eff}	damping factor for integrated structure-foundation model
β_r	Rayleigh damping stiffness coefficient
γ_s	soil unit weight
γ_{foot}	unit weight of footing material
γ_{Rd}	material safety factor of soil
δ_F	fraction of ultimate yield force of shallow foundation
δ_K	fraction of elastic stiffness of shallow foundation
Γ_θ	foundation depth and sidewall influence factor for rotational stiffness

ε	axial strain of soil unconfined compressive test
ε_{50}	axial strain at $0.5\sigma_{ult}$
$\theta(z)$	rotation of pile shaft with depth
θ	foundation rotation
θ_F	rotation of centre of the foundation system
ζ	viscous damping
λ	Winkler pile solution parameter
λcd	depth adjustment factor for cohesive resistance of soil
λci	inclination adjustment factor for cohesive resistance of soil
λcs	shape adjustment factor for cohesive resistance of soil
λqd	depth adjustment factor for surcharge
λqi	inclination adjustment factor for surcharge
λqs	shape adjustment factor for surcharge
$\lambda\gamma d$	depth adjustment factor for frictional resistance of soil
$\lambda\gamma i$	inclination adjustment factor for frictional resistance of soil
$\lambda\gamma s$	shape adjustment factor for frictional resistance of soil
μ	structural ductility factor
ν_s	soil Poisson's ratio
$\xi_{material}$	soil hysteretic damping ratio
ξ_n	fraction of critical damping of mode n
ρ_s	soil density
σ	applied normal stress of soil unconfined compressive test
σ'_0	effective vertical stress in soil
σ_{ult}	soil compressive strength
σ_{v0}	static vertical stress in soil at depth
ϕ_s	soil friction angle
ϕ	curvature of structural section
ϕ_M	mode shape
ψ_c	combination factor for imposed action
ω	excitation frequency
ω_n	frequency of mode n