UNIVERSITY OF TECHNOLOGY SYDNEY

Assessing Impacts of Soil Constitutive Behavior and Water Pressure on Seismic Performance of Buildings on Shallow Foundations

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Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of A/Prof. Behzad Fatahi
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University of Technology Sydney
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September 2020

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Sincerely Dedicated to

My Father and Mother

Reza and *Akram*

ACKNOWLEDGEMENT

First and foremost, I, Navid Yeganeh, would like to express my sincere gratitude to my principal supervisor, Associate Professor Behzad Fatahi, for the continuous support of my PhD study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my PhD study. I would also appreciate my alternative supervisor, Associate Professor Hadi Khabbaz, for his presence and willingness to help during this research work.

I am appreciative of all my friends, and colleagues, as well as the academic and non-academic staffs at the Centre for Built Infrastructure Research (CBIR) of the Faculty of Engineering and Information Technology (FEIT), based in UTS. It was an honor for me to walk through this PhD journey with my comrades, Yang (Alex) Dong, Piyush Punetha, and John Phung.

My appreciation is extended to the High-Performance Computer (HPC) team, Anselm Motha and Matt Gaston, at UTS for their commitment, and extensive assistance. Special thanks to the IT office of FEIT and particularly Jason Chan for providing this research study with the prompt and technical IT support. I also deeply appreciate UTS thanks to conferring the UTS President's Scholarship upon me, without which this research work could have not been possible.

Seizing the moment, I wish to express my heartfelt gratitude to my parents in light of the fact that I owe it all to them.

LIST OF PUBLICATIONS RELATED TO THIS RESEARCH

Journal Articles

Yeganeh, N. & Fatahi, B. 2019, 'Effects of choice of soil constitutive model on seismic performance of moment-resisting frames experiencing foundation rocking subjected to near-field earthquakes', *Soil Dynamics and Earthquake Engineering*, vol. 121, pp. 442-459.

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A	Acceleration coefficient of earthquake
A_0	Reference area in soil-structure relative rigidity
A_f	Area of load-carrying foundation
A_g	Gross cross-sectional area of column
A_s	Cross-sectional area of shear reinforcement
A_t	Cross-sectional area of longitudinal tensile reinforcement
A_v	Effective peak velocity-related acceleration coefficient
a	Representative of maximum value of modulus reduction factor
a_h	Earthquake horizontal peak base acceleration
B	Foundation width
b	Representative of optimum degree of saturation
b_e	Effective foundation size
C	Soil cementation
$\bar{C}$	Viscous damping of building
$C_h(T)$	Spectral shape factor
$C_h(\tilde{T}_{eff})$	Effective spectral shape factor
C_p	P-wave velocity
C_s	S-wave velocity
$\bar{C}_s$	Seismic response coefficient for fixed-base structure
$\tilde{C}_s$	Seismic response coefficient for flexible base structure
c^{mob}	Mobilized cohesion
c_{sd}	Soil dependent parameter

c'	Ultimate effective cohesion
c'_{int}	Effective cohesion of interface element
D	Damping ratio
D_{10}	Effective grain size
D_e	Depth of embedment of foundation
$D_{f=0.1}$	Damping ratio at frequency of 0.1 Hz
D_r	Relative density
D_s	Thickness of relatively uniform soil layer under foundation
D_{sd}	Shortest distance from construction site to nearest fault
DR_{tt}	Total inter-story drift ratio
d	Thickness of any soil layers from 0 to 30 m depth below foundation
d_0	Distance from extreme compressive fibre of concrete cross-section to centroid of outermost layer of tensile reinforcement
d_i	Deflection at $(i)^{th}$ building story
d_{i+1}	Deflection at $(i+1)^{th}$ building story
d_n^{int}	Interface normal displacement
d_s^{int}	Previous shear displacement of interface element
$dp'/d\varepsilon_v$	Loading tangent modulus
E_c	Modulus of elasticity of concrete
E_s	Modulus of elasticity of steel reinforcement
E_{str}	Modulus of elasticity of structural material
e	Soil void ratio
e_b	Basement embedment or foundation embedment
e_b/r_x	Embedment ratio

F_a	Axial compressive force on cross-section of column
f	Loading frequency
f_p	Volumetric yield function
f_q	Shear yield function
f_{fb}	Fundamental frequency of fixed-base building
f_{sy}	Characteristic yield strength of steel reinforcement
f_{su}	Ultimate stress of steel reinforcement
f_{cmi}	Mean in-situ compressive strength of concrete
f_c'	Concrete characteristic compressive strength
G	Soil shear modulus
G_0 or (G_{max})	Small-strain shear modulus or maximum shear modulus
$G_{0(dry)}$	Low-amplitude shear modulus for completely dry condition
G_c	elastic tangent shear modulus
G_{c_i}	Initial elastic tangent shear modulus
G_c^{ref}	Elastic tangent shear modulus at reference mean effective stress
G_d	Dashpot constant
G_i^p	Initial tangent plastic shear modulus
G_m^p	Mobilized plastic shear modulus
G_s	Specific gravity of soil solids
G_{sd}	Strain-degraded shear modulus
G_{sp}	Spring constant
G/G_0	Shear modulus reduction factor
g	Acceleration of gravity
g_p	Volumetric potential function

g_q	Shear potential function
H	Building height
H_s	Soil thickness
h	Story height in building
$\bar{h}$	Effective height of building
h_{bd}	Bedrock depth
H/r_θ	Structure aspect ratio
I	Static moment of inertia of load carrying foundation
I_g	Moment of inertia of uncracked structural section
I_p	Soil plasticity index
J_2	Second deviatoric stress invariant
K	Soil bulk modulus
K_0	At-rest earth pressure coefficient
$K_{0(OC)}$	At-rest earth pressure coefficient for overconsolidated soil
$k(\gamma)$	Decreasing function of cyclic shear strain amplitude
K_θ	Rocking stiffness of foundation
K'	Effective bulk modulus
$\bar{K}$	Initial stiffness of building
K_c	Elastic tangent bulk modulus
K_{cc}	Bulk modulus of concrete
K_{ci}	Initial elastic bulk modulus
K^*_{fixed}	Effective stiffness of Single-Degree-Of-Freedom (SDOF) oscillator
K_l	Lateral stiffness of foundation
K_M	Elasto-plastic bulk multiplier

K_n	Normal spring stiffness
K_p	Plastic bulk modulus
K^{ref}	Slope of laboratory curve in isotropic consolidation test
K_{e-p}^{ref}	Elasto-plastic bulk modulus at reference mean effective stress
K_s	Shear spring stiffness
K_{ss}	Soil-structure relative rigidity
K_t	Translational stiffness of foundation
K_u	Undrained bulk modulus
K_w	Water bulk modulus
k	Material constant from regression analysis
k_h	Horizontal seismic coefficient
k_h^*	Critical acceleration
k_p	Probability factor
L	Logarithmic strain
L_0	Foundation length in direction of analysis
L_1 & L_2	Calibrated parameters for hysteretic damping
l	Height of cross-section of structural element
M	Total mass of building
M^*	Effective mass of building for first mode of vibration
M_e	Mass of fixed-based building
M^p	Limiting plastic moment
M_s	Normalized secant modulus
M_t	Normalized tangent modulus
$m(\gamma)$	Increasing function of cyclic shear strain amplitude

N	Number of loading cycles
N_{cE}, N_{qE}, & $N_{\gamma E}$	Seismic bearing capacity factors
N_{cS}, N_{qS}, & $N_{\gamma S}$	Static bearing capacity factors
N_{bl}	Number of building spans in longitudinal direction
N_{bt}	Number of building spans in transversal direction
N_{max}	Maximum near-fault factor
N_s	Number of stories
n	Soil porosity
$\bar{n}$	Shear wave velocity reduction factor
n_c	Number of columns at story under analysis
OCR	Overconsolidation ratio
p'	Mean effective stress
p_{atm}	Atmospheric pressure
p^{cap}	Cap pressure
p_i^{cap}	Initial cap pressure
p^{ref}	Reference mean effective stress
q	Deviator stress
R	Response modification factor
R_F	SDOF strength reduction factor
R_f	Failure ratio
R_M	Practical site and interaction-dependent MDOF modification factor
R_p	Return period factor
RRS_{bsa}	Base-slab averaging effect
RRS_e	Ratio of response spectra for embedment

r, r_a & r_m	Characteristic foundation lengths
r_{eq}	Radius of equivalent circular foundation
r_f	Radius of foundation
r_x	Equivalent foundation radius for translation
r_θ	Equivalent foundation radius for rotation
S	coefficient related to soil profile characteristics of site
S_a	Spectral acceleration
$S_{a_{max}}$	Maximum response acceleration
$\bar{S}_a$	Mean spectral acceleration
$\tilde{S}_a$	SSI adjusted spectral response acceleration
S_{D1}	Design earthquake spectral response acceleration at 1-s period
S_{DS}	Design earthquake spectral response acceleration at short period
S_r	Degree of saturation
$S_{r(opt)}$	Optimum degree of saturation
S_s	Center-to-center spacing of shear reinforcement
S_u	Undrained shear strength of soil
$\bar{S}_v$	Mean spectral velocity
s	Slenderness ratio of building
T	Structural period
T_2	Second mode period of soil-structure system
$\tilde{T}$ & $\tilde{T}_{eff}$	Effective period of flexible base building
T_h	Natural period of rigid-body translation of structure
T_{int}	Limiting tensile strength of interface element
T_L	Long-period transition period

T_n	Total normal boundary traction
T_n^{ab}	Resistant traction of dashpot in normal direction
T_n^{ff}	Normal component of free field traction
T_r	Natural period of rocking of structure
T_s	Total shear boundary traction
$\bar{T}_s$	Characteristic site period
T_s^{ab}	Resistant traction of dashpot in shear direction
T_s^{ff}	Shear component of free field traction
T_{SSI}	Fundamental period of soil-structure system
$\tilde{T}_{eff}/T_{eff}$	Effective period-lengthening ratio
t_g	Geologic age
t_n	Normal resistant traction of viscous dashpot
t_s	Shear resistant traction of viscous dashpot
u	Pore water pressure
u_{dyn}/σ_v'	Excess pore water pressure ratio
V	Fixed-base structure's seismic base shear
$\tilde{V}$	Adjusted base shear for soil-structure interaction
V_c	Velocity coefficient of earthquake
V_i	Vector component of velocity
V_u	Story shear capacity
V_{MDOF}	Base shear demand of inelastic flexible base MDOF system
V_s	Soil shear wave velocity
$V_{s,30}$	Average shear wave velocity of top 30 m of soil deposit
$V_{s@b_e}$	Weighted average shear wave velocity within depth of b_e

$\bar{V}_{s,i}$	Weighted average of in-situ shear wave velocity
V_{SDOF}	Base shear demand of fixed-base SDOF system
v_n	Normal component of velocity at lateral boundary
v_n^{ff}	Normal component of velocity of grid point in side free field
v_s	Shear component of velocity at lateral boundary
v_s^{ff}	Shear component of velocity of grid point in side free field
$\bar{W}$	Effective seismic weight of building
W_l	Dissipated energy in cycle of loading
W_{ms}	Stored maximum strain energy during one cycle
W_t	Total weight of building
W_i/g	Mass assigned to $(i)^{th}$ building story
Z	Earthquake hazard factor
α_0	Structure-to-soil stiffness ratio
α_1, α_2, & α_3	Calibrated parameters for hysteretic damping
$\bar{\alpha}$	Relative weight density of structure and underlying soil
α_L	Local damping coefficient
α_y	Dynamic foundation stiffness modifier for translation
α_θ	Dynamic foundation stiffness modifier for rocking
β	Elastic-plastic coupling coefficient
β_0	Effective damping ratio of soil-structure interaction
$\tilde{\beta}$	Fraction of critical damping for structure-foundation system
β_f	Foundation damping factor
β_{f_H}	Soil hysteretic damping ratio
β_{f_R}	Radiation damping-induced foundation damping

β_i	Fixed-base damping ratio
Γ_{tm}	Normalized tangent modulus
γ	Cyclic shear strain amplitude
$\dot{\gamma}$	Cyclic shear strain rate
$\gamma_{dyn_{min}}$	Minimum cyclic shear strain amplitude
γ_s	Unit weight of soil
γ_{SA}	Single-amplitude cyclic shear strain
γ_{td}	Degradation strain threshold
γ_{tf}	Flow threshold
γ_{tl}	Linear threshold shear strain
γ_{tv}	Volumetric cyclic threshold strain
Δd_s^{int}	Incremental shear displacement of soil-foundation interface
ΔT	Additional period due to soil-structure interaction
Δt	Time interval
Δu	Excess pore water pressure build-up
ΔV	Base shear reduction due to soil-structure interaction
Δz_{min}	Smallest width of adjoining zone to soil-foundation interface
$\Delta \varepsilon$	Strain increment
$\Delta \varpi$	Dissipated energy per oscillation cycle
δ	Lateral story deflection in fixed-based building
$\tilde{\delta}$	Lateral story deflection under influence of soil-structure interaction
δ_{ij}	Kronecker delta
ε_s^p	Plastic shear strain
$\dot{\varepsilon}_s^p$	Rate of plastic shear strain

ε_{su}	Ultimate strain of steel reinforcement
ε_v	Volumetric strain
ε_v^p	Irrecoverable volumetric strain
$\dot{\varepsilon}_v^p$	Rate of plastic volumetric strain
ζ	Critical damping
ζ_h	Soil damping ratio for translational mode of foundation
ζ_r	Soil damping ratio for rocking mode of foundation
η_f	Failure stress ratio
η^{mob}	Mobilized stress ratio
η_{ult}	Ultimate stress ratio
θ	Inter-story drift coefficient
θ_l	Lode's angle
κ	Recompression Index
κ_1	Stress dependency exponent
κ_2	Plasticity index-dependent exponent
Λ_i	Numerical grid point location in soil medium
λ	Compression index
$\bar{\lambda}$	User-defined analysis type factor
μ	Ductility demand
μ_s	Ductility demand of soil-structure system
μ_t	Predefined target ductility demand
$\tilde{\mu}_u$	Global ductility of equivalent oscillator of actual structure
ν	Soil Poisson's ratio
ν'	Effective Poisson's ratio

ν_c	Poisson's ratio of concrete
ν_u	Undrained Poisson's ratio
ρ	Soil mass density
ρ_c	Concrete density
ρ_{eff}	Soil effective density
ρ_s	Steel reinforcement density
ρ_w	Water density
σ^{ff}	Free field normal stress
σ_y	Yield stress of concrete material
$\sigma'_{n,int}$	Effective normal stress at foundation-soil interface
σ'_{pc}	Vertical preconsolidation pressure
σ'_v	In-situ effective overburden stress
τ	Shear stress
$\bar{\tau}$	Normalized shear stress
τ^{ff}	Free field shear stress
$\tau_{f,int}$	Interface shear strength
τ_{int}	Shear stress at foundation-soil interface
τ/τ_f	Cyclic shear stress ratio
φ^{mob}	Mobilized friction angle
φ'	Soil effective friction angle
φ'_f	Failure effective friction angle
φ'_{int}	Effective friction angle of foundation-soil interface
$\emptyset_i$	Amplitude of first mode of vibration at $(i)^{th}$ building story
χ	Threshold cyclic shear stress ratio

ψ	Dilatancy
ψ_f	Failure dilation angle
ψ^{mob}	Mobilized dilation angle
Ω	Active Coulomb wedge angle
ω	Width of cross-section of structural element
ϖ	Maximum strain energy

ABSTRACT

The growing need for the high rise buildings in the megalopolises necessitates the reliable predictions of the buildings' performance amidst the earthquakes with the aim of curtailing the severe damage and probable partial or the total collapse of the superstructures. The seismic excitation, experienced by the superstructures, is a function of the seismic source, travel path and local site effects, as well as the Soil-Structure Interaction (SSI) influences. Thus, the undeniable paramountcy of the dynamic soil-structure interaction is evident.

This thesis conducts the three-dimensional elasto-plastic-based coupled SSI numerical simulations in FLAC3D using the direct method with the help of the High-Performance Computer (HPC) at University of Technology Sydney (UTS), taking averagely a few days to a month. The 15-story and 20-story reinforced concrete moment-resisting buildings, as the examples of the typical high rise buildings in the relatively high-risk earthquake-prone zones, are designed considering the relevant Australian codes and in line with the constructability and norms. The plastic moment concept is employed to assign the elastic-perfectly plastic model to the superstructures and their mat foundations. The geometric nonlinearity of the adopted superstructures, capturing the $P - \Delta$ effect, is accommodated by the use of the large-strain solution mode. The dependency of the soil shear modulus and corresponding damping ratio on the seismically-induced shear strains is also captured. The interaction between the soil mass and building foundation is simulated by the use of the advanced interface element, mimicking the possible sliding, separation, and gapping. The cherry-picked near-field earthquake excitations are scaled by means of the response spectrum matching method.

The medium, underneath the engineering superstructures, influences their dynamic responses. An investigation on the impact of the soil dynamic properties, including the shear wave velocity and small-strain shear modulus, on the seismic performance of the

superstructures, supported by a shallow foundation, is conducted. The outcomes show that these soil properties ought to be served with the acute care in any seismic soil-foundation-structure interaction simulation so as to obtain the reliable results. Taking a step further, the variations of the degree of saturation, stemming from the extensive dry climate and floods, could impair the seismic performance of the mat-supported buildings due to exceeding the life safety drift limit, hinging around the post-earthquake damage state. The damp soils are basically softer and so absorb more energy than the dry, stiff soils. After a dry season, during a seismic event, the selected building in this study will experience more load, will move more, will crack more and ultimately will be unsafe whether it remains standing or collapses.

This thesis conducts a host of seismic SSI analyses with the consideration of the hardening hyperbolic concept. It is concluded that incorporating more advanced soil plasticity models, suitable for the seismic analyses of the soil-structure systems, could predict the foundation rocking and structural lateral deflections more accurately, both of which must be strictly overseen in the application of the foundation rocking isolation technique. Examining the geotechnical and structural objectives in this study exhibits that the presence of the water table at the construction site had better not be dismissed in any case as the generation of the excess pore water pressure could markedly weaken the seismic performance of the superstructures by pushing it from the life safety state to the near collapse damage level or even the collapse state. In practice, however, the consideration of the presence of the water table at the construction site is only limited to the drained analysis and undrained shear strength analysis.

The design and practicing engineers, stakeholders, and practitioners are meant to consider the Performance-Based Seismic Design (PBSD) approach as an indicator of the buildings' performance, subjected to the different levels of the earthquakes. This thesis is devoted to provide them with a clear understanding on the key factors, affecting the relations between SSI, PBSD, and the foundation rocking since an ounce of prevention is worth a pound of cure.