Effect of Dynamic Soil-Pile-Structure Interaction on Seismic Response of Mid-Rise Moment Resisting Frames

By

Aslan Sadeghi Hokmabadi

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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(Aslan Sadeghi Hokmabadi)

Sydney, June 2014

Sincerely Dedicated to

My Father and Mother

Samad and Sorayyah

ABSTRACT

Seismic behaviour of structures built on soft soils is influenced by the soil properties and the foundation type, where the response is significantly different from the fixed base condition owing to the interaction between the ground and the structure. Soil-Structure Interaction (SSI) reduces the natural frequency of the system and increases the effective damping ratio of the system, for typical soils and foundations, in comparison with the fixed-base structure. This can considerably alter the response of the building frames under the seismic excitation by influencing the structural demand of the building as well as amplifying the lateral deflections and inter storey drifts of the superstructure. This amplification of lateral deformations due to SSI may change the performance level of buildings in the performance based design approach, which should be considered with great rigor accounting for the influence of SSI significantly influenced by the foundation type (i.e. shallow and deep foundation), in order to provide safe and cost effective design against the natural disasters such as earthquake.

In this study, in order to provide a benchmark to verify and calibrate the numerical model as well as experimentally investigate the influence of SSI on the seismic response of buildings, a series of shaking table tests on the soil-foundation-structure models are conducted at the University of Technology Sydney (UTS) structures laboratory. Different foundation types such as shallow foundation, floating pile foundation, end-bearing pile foundation as well as fixed base condition, excluding SSI interaction, are physically modelled. A laminar soil container is designed and constructed to simulate the free field soil response by minimising boundary effects. Simulating the superstructure as a multi-storey frame during the shaking table tests makes experimental data unique. Accordingly, in the current shaking table tests, by adopting the same soil properties, same superstructure, same input motions, and same test setup, a clear comparison is provided between the structural responses for different types of foundations. The experimental results indicate that soil-structure interaction amplifies the lateral deflections and inter-storey drifts of the structures supported by different types of foundations. However, the choice of the foundation type influences the structural performance significantly and should be addressed carefully in investigating the influence of SSI on the superstructure response during shaking excitations.

A fully nonlinear three-dimensional numerical model employing FLAC3D is developed to perform time-history analysis and simulate the performance of the superstructure considering the seismic soil-structure interaction. Hysteretic damping of the soil is implemented to represent the variation of the shear modulus reduction factor and the damping ratio of the soil with the cyclic shear strain. Free field boundary conditions are assigned to the numerical model and appropriate interface elements, capable of modelling sliding and separation between the pile and soil elements, are considered. The developed numerical model is verified and validated against the conducted shaking table results. Comparison of the numerical predictions and the experimental data shows a good agreement confirming the reliability of the numerical model. Consequently, the proposed numerical model is a reliable method of simulation which can be employed for further numerical investigations concerning the dynamic soil-structure interaction. Practicing engineers can adopt this verified numerical modelling procedure in the design to consider the effect of SSI.

Furthermore, in order to investigate the different characteristics of SSI and its influence on the seismic response of superstructures, parametric studies with respect to different types of foundations are conducted employing the previously verified three-dimensional numerical modelling procedure. A full scale fifteen storey structure (prototype) with four different types of foundations, namely, (i) fixed-base structure representing the situation excluding the soil-structure interaction, (ii) structure supported by a shallow foundation, (iii) structure supported by a pile-raft foundation in soft soil, and (iii) structure supported by a floating (frictional) pile foundation in soft soil, are simulated. According to the results of the numerical investigations, the properties of the in situ soil influence the characteristics of the excitation in terms of peak acceleration and frequency content. Moreover, the reduction ratio of the shear forces of superstructure due to SSI is a function of the foundation type, while the magnitude of this reduction is different for different levels in the superstructure. Accounting for the rocking-dissipation concept, results of this study can help the practicing engineers in selecting the proper foundation type for the structures. The foundation types experiencing considerable amount of rocking during an earthquake, dissipate significant amount of earthquake energy in comparison with the other types of foundations, and this rocking-dissipation in turn results in directing less shear forces to the superstructure and reducing the structural demand of the superstructure.

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LIST OF REFEREED PUBLICATIONS BASED ON THIS RESEARCH

Journal Articles

1. **HOKMABADI, A. S.**, FATAHI, B. & SAMALI, B. 2014. Physical modelling of seismic soil-pile-structure interaction for buildings on soft soils. *International Journal of Geomechanics,* (DOI: 10.1061/(ASCE)GM.1943-5622.0000396).
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A	Area
A_{loop}	Area of the hysteresis loop
a	foundation width
c	damping coefficient of the structure
C	cohesion
$[C]$	damping matrix
c_h	horizontal damping coefficient of the subsoil
c_θ	rocking damping coefficient of the subsoil
C_s	seismic design coefficient of the fixed-based structure
$\widetilde{C}_s$	seismic design coefficient of the flexible-based structure
D	dilation angle
E	modulus of elasticity (Young modulus)
E_s	soil subgrade reaction
f	natural frequency of fixed base structure
$\widetilde{f}$	natural frequency of soil-structure system
f'_c	specified compressive strength
f_m	natural frequency of the model
f_p	natural frequency of the prototype
F_s	shear force
F_n	normal force
F_x	unbalanced forces in x direction from the free-field grid
F_y	unbalanced forces in y direction from the free-field grid
F_z	unbalanced forces in z direction from the free-field grid
F^{ff}_x	free-field grid point forces in x direction
F^{ff}_y	free-field grid point forces in y direction
F^{ff}_z	free-field grid point forces in z direction
$\{F_v\}$	force vector
G	shear modulus of the soil
G_0	shear modulus of the soil at small strains
G_{max}	largest value of the shear modulus

G_{sec}	secant shear modulus
G_{tan}	tangent shear modulus
g	gravity
h	height of the structure
$h\theta$	lateral displacement at the top of the structure due to rotation of the base
I	moment of inertia
I_c	flexural rigidity of the building columns
I_x	second moment of inertia with respect to x-axis
I_y	second moment of inertia with respect to y-axis
I_z	second moment of inertia with respect to z-axis
J	polar moment of inertia
I_r	moment of inertia for rocking motion
k	stiffness of the structure
k_s	shear spring stiffness
k_n	normal spring stiffness
k_y	lateral stiffness of foundation
k_θ	rocking stiffness of foundation
k_h	horizontal stiffness coefficient of the subsoil
$\bar{k}$	stiffness of a fixed-base structure
K	bulk modulus
$[K]$	stiffness matrix
K_h	horizontal stiffness coefficient of the subsoil
K_r	rocking stiffness coefficient of the subsoil
k_x	lateral stiffness of the subsoil foundation
L	effective contact length
m	mass of the structure
$[M]$	mass matrix
M_p	plastic moment capacity
M_0	overturning moment
M_s	secant modulus
M_t	tangent modulus
P_x	axial load on pile
r	radius of the foundation base
S	slider

S_u	shear strength
S_p	performance factor
S_u	soil shear strength
S_{DS}	design earthquake motion
T	natural period of fixed-base structure
$\tilde{T}$	natural period of soil-structure system
T_s	tensile strength
u	lateral displacement at the top of the structure due to structural distortion
u_n	incremental relative displacement vector in normal direction
u_s	incremental relative displacement vector in shear direction
u_0	lateral displacement at the top of structure due to translation of the base
u_t	total displacement of the base
u_g	horizontal seismic excitation
$\tilde{u}^g$	effective input motion
$\{u\}$	nodal displacement
$\{\dot{u}\}$	nodal velocity
$\{\ddot{u}\}$	nodal acceleration
V	base shear of fixed base structure
$\tilde{V}$	base shear of the structure in soil-structure system
ΔV	decrease in the base shear due to SSI
V_p	compression wave velocity of the soil
V_s	shear wave velocity of the soil
V_{s0}	shear wave velocity of the soil at small strains
W_D	dissipated energy in one hysteresis loop
W_S	maximum strain energy
$\overline{W}$	effective seismic weight of structure
y	lateral deformation of pile at point x
Δz_{min}	smallest width of the adjacent zone in the normal direction
γ	shear strain
γ_{ref}	numerical fitting parameter
δ	maximum lateral deflection of fixed base structure
$\tilde{\delta}$	maximum lateral deflection of the structure in soil-structure system

Δt	time-step
ΔS_y	mean vertical zone size at boundary grid point
η	material viscosity
θ	foundation rotation
λ	geometric scaling factor
λ_p	density scaling factor
λ_ε	strain scaling factor
υ	Poisson's ratio
v_x^m	*x*-velocity of the grid point in the main grid
v_y^m	*y*- velocity of the grid point in the main grid
v_z^m	*z*- velocity of the grid point in the main grid
v_x^{ff}	*x*-velocity of the grid point in the free-field grid
v_y^{ff}	*y*- velocity of the grid point in the free-field grid
v_z^{ff}	*z*- velocity of the grid point in the free-field grid
ξ	equivalent viscous damping ratio
$\tilde{\xi}$	effective damping ratio
ξ_g	hysteretic material damping of the soil
ρ	soil density
σ_y	yield stress
σ_{xx}^{ff}	mean horizontal free-field stress at the grid point
σ_{xy}^{ff}	mean free-field shear stress at the grid point
ϕ	friction angle
$\tilde{\omega}$	effective natural frequency
ω_0	natural frequency of the fixed base structure
τ	shear stress
$\bar{\tau}$	normalised shear stress