Determining Seismic Response of Mid-rise Building Frames Considering Dynamic Soil-Structure Interaction

By

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

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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ABSTRACT

Structures are often mounted on layers of soil unless bedrock is very close to the ground surface. Based on the fact that seismic waves pass through kilometres of bedrock and usually less than 100 meters of soil, soil layers play a significant role in assigning the characteristics of the ground surface movement. When the ground is stiff enough, the dynamic response of the structure will not be influenced significantly by the soil properties during the earthquake, and the structure can be analysed under the fixed base condition. When the structure is resting on a flexible medium, the dynamic response of the structure will be different from the fixed base condition owing to the interaction between the soil and the structure. This difference in behaviour is because of the phenomenon, commonly referred to as soil-structure interaction (SSI), which if not taken into account in analysis and design properly; the accuracy in assessing the structural safety, facing earthquakes, could not be reliable. Performance-based engineering (PBE) is a technique for seismic evaluation and design using performance level prediction for safety and risk assessment. Soil-structure interaction particularly for unbraced structures resting on relatively soft soils may significantly amplify the lateral displacements and inter-storey drifts. This amplification of lateral deformations may change the performance level of the building frames. Thus, a comprehensive dynamic analysis to evaluate the realistic performance level of a structure should consider effects of SSI in the model.

In this study, an enhanced numerical soil-structure model has been developed which treats the behaviour of soil and structure with equal rigor. Structural elements of the soil-structure model are capable of capturing both elastic and inelastic structural behaviour as well as structural geometric nonlinearity (large displacements) in dynamic analysis. Adopting direct method of analysis, the numerical model can perform fully nonlinear time history dynamic analysis to simulate realistic dynamic behaviour of soil and structure under seismic excitations accurately. Fully nonlinear method precisely follows any prescribed nonlinear constitutive relation and adopts hysteretic damping algorithm enabling strain-dependent modulus (G/G_{max} - γ) and damping functions (ξ - γ) to be incorporated directly to capture the hysteresis curves and energy-absorbing characteristics of the real soil. In order to avoid reflection of outward propagating waves back into the model, viscous boundaries comprising independent dashpots in the normal and shear directions are placed at the lateral boundaries of

the soil medium. In addition, the lateral boundaries of the main grid are coupled to the free-field grids at the sides of the model to simulate the free-field motion which would exist in the absence of the structure.

The proposed numerical soil-structure model has been verified and validated by performing experimental shaking table tests at the UTS civil laboratories. For this purpose, a prototype soil-structure system including a building frame resting on a clayey soil has been selected and scaled with geometric scaling factor of 1:30. The soil-structure physical model consists of 15 storey steel structural model, synthetic clay mixture consists of kaolinite, bentonite, class F fly ash, lime, and water, and laminar soil container, designed and constructed to realistically simulate the free field conditions in shaking table tests. A series of shaking table tests were performed on the soil-structure physical model under the influence of four scaled earthquake acceleration records and the results, in terms of maximum structural lateral and vertical displacements, were measured and compared with the numerical predictions. Comparing the predicted and observed values, it is noted that the numerical predictions and laboratory measurements are in a good agreement. Therefore, the numerical soil-structure model can replicate the behaviour of the real soil-structure system with acceptable accuracy.

In order to determine the elastic and inelastic structural response of regular mid-rise building frames under the influence of soil-structure interaction, three types of mid-rise moment resisting building frames, including 5, 10, and 15 storey buildings are selected in conjunction with three soil types with the shear wave velocities less than 600m/s, representing soil classes C_e (V_s=600*m/s*), D_e *(Vs=320m/s)*, and E_e *(Vs=150m/s)* according to Australian Standards, having three bedrock depths of 10, 20, and 30 metres. The structural sections are designed after conducting nonlinear time history analysis, based on both elastic method, and inelastic procedure considering elastic-perfectly plastic behaviour of structural elements. The designed frame sections are modelled and analysed, employing Finite Difference Method adopting FLAC2D software under two different boundary conditions: (i) fixed base (no soil-structure interaction), and (ii) flexible base considering soil-structure interaction. Fully nonlinear dynamic analyses under the influence of four different earthquake records are conducted and the results in terms of lateral displacements, inter-storey drifts, and base shears for both mentioned boundary conditions are obtained, compared, and discussed. According to the numerical and experimental investigations, conducted in this study, soil-structure interaction has significant effects on the elastic and inelastic seismic response and performance level of mid-rise moment resisting building frames resting on soil classes D_e and E_e. Thus, the conventional elastic and inelastic design procedures excluding SSI may not be adequate to guarantee the structural safety of regular mid-rise moment resisting building frames resting on soft soil deposits.

Based on the numerical results, a simplified design procedure is proposed in which inter-storey drifts under the influence of soil-structure interaction for each two adjacent stories can be determined and checked against the criterion of life safe performance level. This can be used to ensure the performance levels of the mid-rise moment resisting building frames under the influence of SSI remain in life safe level, and the seismic design is safe and reliable. Structural engineers and engineering companies could employ the proposed simplified design procedure for similar structures as a reliable and accurate method of considering SSI effects in the seismic design procedure instead of going through the whole numerical procedure which could be complicated and time consuming.

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LIST OF REFEREED PUBLICATIONS BASED ON THIS RESEARCH

Journal Articles

1. **Tabatabaiefar, H.R.**, Fatahi, B. & Samali, B. 2012, 'Seismic Behaviour of Building Frames Considering Dynamic Soil-Structure Interaction', *International Journal of Geomechanics*, ASCE, doi:10.1061/ (ASCE) GM.1943-5622.0000231 (Accepted on June 5, 2012).
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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF NOTATIONS

A foundation area

B foundation width

c damping coefficient of the structure

C cohesion

$[C]$ damping matrix

C_h horizontal damping coefficient of the subsoil

C_r rocking damping coefficient of the subsoil

E modulus of elasticity

E_{str} modulus of elasticity of the structural material

f natural frequency of fixed base structure

$\tilde{f}$ 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 total shear force

F_n total 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

$\{F_v\}$ force vector

G shear modulus of the soil

G_{max} largest value of the shear modulus

h height of the structure

h_s bedrock depth

$h\theta$ lateral displacement at the top of the structure due to rotation of the base

I_c flexural rigidity of the building columns

I_r moment of inertia for rocking motion

k stiffness of the structure

k_s shear spring stiffness

k_n normal spring stiffness

K bulk modulus

$[K]$ stiffness matrix

K_h horizontal stiffness coefficient of the subsoil

K_r rocking stiffness coefficient of the subsoil

K_{ss} soil-structure relative rigidity

k_x lateral stiffness of the subsoil foundation

k_θ rocking stiffness of the subsoil foundation

L effective contact length

m mass of the structure

$[M]$ mass matrix

M_p plastic moment capacity

N_s number of stories

r radius of the foundation base

S_p performance factor

S_u soil shear strength

T natural period of fixed-base structure

$\tilde{T}$ natural period of soil-structure system

T_n normal traction at the model boundaries

T_s shear traction at the model boundaries

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_0^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

V_p compression wave velocity of the soil

V_s shear wave velocity of the soil

W_D dissipated energy in one hysteresis loop

W_S ### maximum strain energy

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 analysis type factor

μ structural ductility factor

υ Poisson's ratio of the soil

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_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

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_s natural frequency of the fixed base structure